The TREND IN ENGINEERING

at the University of Washington

In this issue:

ANALYTICAL ASPECTS OF X-RAY DIFFRACTION

IMPORTANCE OF CROSSWIND FORCES OBTAINABLE FROM MOVING WING SYSTEMS

THERMODYNAMIC PROPERTIES OF ANILINE

SEQUENTIAL WORK SAMPLING

January, 1954

Published quarterly

by

THE ENGINEERING EXPERIMENT STATION

ORGANIZED TEAMWORK IN BASIC RESEARCH

"What are the limitations of the organized teamwork method of research? Can it be effectively applied in carrying forward basic, fundamental, scientific inquiries? It has been questioned, for example, whether the teamwork method, which has unquestionably been proved effective and powerful in the type of applied research important to industry, can be expected to supersede the efforts of the inspired, individual worker in the realm of pure scientific research.

"The older generation of natural scientists—notably such British giants of the 19th century as Tyndall and Huxley—insisted that he who hopes to be successful in uncovering Nature's secrets must search in a humble spirit animated solely by a desire for truth and with no thought in mind of rewards or of the ultimate use, if any, to which the truths revealed may be put. . . . Clearly, the motive back of industrial research is quite different. . . . Yet this does not necessarily mean . . . that the methods which have proved so valuable in industrial research cannot be applied to research in pure science. . . . Motives differ, but methods may have values which are independent of motive.

"On the one hand, the industrial researcher seeks answers to specific industrial problems and cannot ignore the fact that he is expected to show a reasonable probability of—must, indeed, in the long run, produce—financial returns commensurate with the costs of his searches. It is clear that few, except, perhaps, some of our major industries, can afford free-roving individual workers and gamble on the remote possibility that, sooner or later, they may turn up with a discovery which will be of value to that particular industry.

"When it comes to writing a prescription for research, therefore, the doctors differ. There is the apparently incurable romantic group which insists that scientific truths come to us as special revelations granted to the very rare, inspired, self-sacrificing, and faithful scientific worker in a magical 'flash of genius.' There are others who hold to the statement, attributed to Edison, that genius is 1 per cent inspiration and 99 per cent perspiration. Important discoveries both in pure science and in engineering science and industry have been made by both methods. For example, Langmuir's work with the General Electric Company in the development of the gas-filled electric lamp may be cited as an example of the value to industry of research which stemmed from a spirit of scientific curiosity, and began as an inquiry in pure science. Morgan's epoch-making discoveries in genetics on the other hand, were made possible through organized teamwork. Industrial research, it is true, does aim to anticipate the possible discoveries of individuals through teamwork—but, here again, notable industrial advances—new products and processes—are still being developed by individual, independent inventors, although it seems certain that, as the equipment essential to productive research increases in scope and cost, the isolated inventor will face increasing difficulties.

"We are reminded, in this connection, of an observation by the British author Hilaire Belloc . . . 'The conquests of physical science,' he observes, 'have been due to the minute and extensive observations conducted by vast numbers of men, and,' he concludes, 'therefore, for the most part by the unintelligent'. . . .

"In this statement Belloc was contrasting the remarkable result stemming from the work of many with the great-man theory of history—the idea embodied in the famous statement of Marshall Foch, that it was not an army that crossed the Alps, it was Hannibal. We may not like Belloc's use of the word 'unintelligent,' but he put his finger on a truth which constitutes the major element of strength and power in science and engineering—the power of an ever-growing body of scientific and technical knowledge and understanding, and the fact that not only the individual genius but vast numbers of men of less than extraordinary gifts can add, through organized research, their bit to this ever-accumulating power. . . In science and engineering, thousands of workers, known and unknown, have played a part in building the huge accumulation of knowledge and experience from which the power of technology stems. It is precisely on this fact that modern organized and directed scientific and engineering research relies."—James Kip Finch in *Engineering and Western Civilization*, New York, McGraw-Hill Book Company, Inc., 1951, pp. 311-13.

THE ENGINEERING EXPERIMENT STATION of the University of Washington was established in December, 1917, to coordinate investigations in progress and to facilitate the development of engineering and industrial research in the University. Its purpose is to aid in the industrial development of the state and nation by scientific research and by furnishing information for the solution of engineering problems.

The scope of the work is three-fold:

(1) to investigate and publish information concerning engineering problems of a more or less general nature that would be helpful in municipal, rural, and industrial affairs;

(2) to undertake extended research and to publish reports on engineering and scientific problems;

(3) to provide opportunities for graduate engineers to conduct research under conditions that will most effectively prepare them for professional service.

For administrative purposes the work of the Station is organized into nine divisions:

1. Aeronautical Engineering
2. Chemical Engineering, Industrial Chemistry
3. Civil Engineering
4. Electrical Engineering
5. Forest Products
6. Geology
7. Mechanical Engineering
8. Mining, Metallurgical, Ceramic Engineering
9. Physics Standards and Tests

The control of the Station is vested in a Station Board consisting of the President of the University, the Dean of the College of Engineering as chairman, the Director of the Station, and members of the faculty, representative of the administrative divisions. The Board determines the character of the investigations to be undertaken and supervises the work.

The Station offers a substantial number of research fellowships to highly qualified graduate students who work under the direct supervision of the faculty of the various divisions. Results of major investigations are published in the form of bulletins and reports. Current research findings from the Station's fellowship projects, as well as accounts of its activities, appear in the quarterly journal, *The Trend in Engineering at the University of Washington*. Reprints of articles by members of the engineering faculty and graduate students published in recognized technical journals are also issued by the Station. Requests for copies of the publications and inquiries for information on engineering and industrial problems should be addressed to the Director, Engineering Experiment Station, University of Washington, Seattle 5.

January, 1954

The TREND IN ENGINEERING

Vol. 6 No. 1

at the University of Washington

Published quarterly in January, April, July, and October, by the Engineering Experiment Station at the University of Washington to reflect the current highlights of its accomplishments and to report progress in its program of investigation and research.

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127 More Hall
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Entered as second-class matter March 7, 1949, at the post office at Seattle, Washington, under the act of August 24, 1912.

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FIG. 1. X-RAY DIFFRACTION AND SPECTROSCOPIC UNIT

B. S. R. Sastry, Research Assistant in the Engineering Experiment Station, is adjusting the diffractometer. In the center is the X-ray spectrograph, and at the right, the electronic control unit and recorder.

Analytical Aspects of X-Ray Diffraction

JAMES I. MUELLER
Associate Professor of Ceramic Engineering

J. I. Mueller

The rapid advancement of the relatively new science of X rays has caused many of its potential applications to be either overlooked or neglected. In the main, this is due to the fact that too few workers in the fields of pure and applied science are aware of the possibilities of this tool. Therefore a review of some of the fundamentals and a discussion of a few of the applications may be timely.

The use of X-ray diffraction and fluorescent X-ray spectrographic techniques is becoming increasingly important in research and control in many branches of mineral industry. Applications in the fields of metallurgy, mining and prospecting, mineral preparation, and ceramics have reached the point where, today, a modern, up-to-date diffraction laboratory is recognized as one of the necessary facilities for teaching in these fields. (See Fig. 1.)

Fundamentals

X rays are part of the electromagnetic spectrum and are similar to ordinary light rays in that they exhibit the properties of refraction, diffraction, and interference. A complete discourse on the generation and properties of X rays is not within the scope of this paper, which will be limited to a brief explanation of diffraction phenomena.

Diffraction is actually part of the phenomenon of scattering. The formulation and explanation has been simplified by Bragg's analogy with the reflection of ordinary light from a mirrored surface, i.e., considering that the array of atoms within a crystal forms a series of parallel planes, the normal distance between these being noted by the symbol, d. (See Fig. 2.) Inasmuch as this d spacing depends upon the size of the atoms making up the crystals and the class in which the material crystallizes, it becomes evident that no two materials have an identical set of d spacings. This, together with the fact that certain extinction laws prohibit all planes from giving a reflection of the incident X-ray beam, makes it possible to use the d spacing pattern as a "finger print" of the crystal.

The Bragg law is based on the fact that the path difference between the portion of the incident X-ray beam reflected by the successive planes must be equal to an integral number of wave lengths in order that the diffracted beam will be reinforced. (See Fig. 2.) This law is stated as follows:

$$n\lambda = 2d \sin \theta$$

where

n = order of diffraction (1, 2, 3, etc.),
λ = wave length of the incident radiation,
d = interplanar spacing,
θ = diffraction angle.

In the application of X-ray spectroscopy still another phenomenon must be considered. When a primary X-ray beam strikes an absorbing material with sufficient energy to eject an inner orbital electron from the atoms making up the absorber, a secondary X-ray photon, whose wave length is characteristic of the absorbing material, is emitted. By diffracting this secondary (fluorescent) X-ray beam by means of a single crystal, we can again apply the Bragg law, and by measuring the diffraction angle, θ, we can determine the wave lengths present in the spectrum. These can then be compared to known wave lengths to determine the composition of the material.

The chief advantages of X-ray spectroscopy over optical spectroscopy are that (1) a much larger sample may be utilized, (2) the concentration of the material is unimportant, (3) the X-ray spectrum has fewer lines than the visible spectrum, and (4) analysis is independent of the physical state of the element.

Uses of X-Ray Diffraction

Qualitative Analysis

Probably the greatest use of X-ray diffraction has been in the analysis of powder samples to determine the crystalline constituents present. The method is

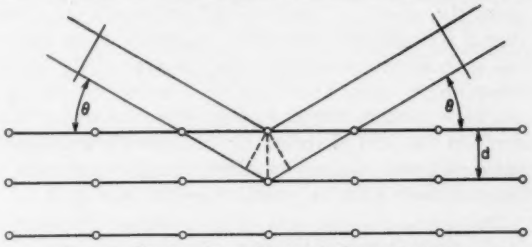


FIG. 2. DIAGRAM OF BRAGG'S RELATIONSHIP

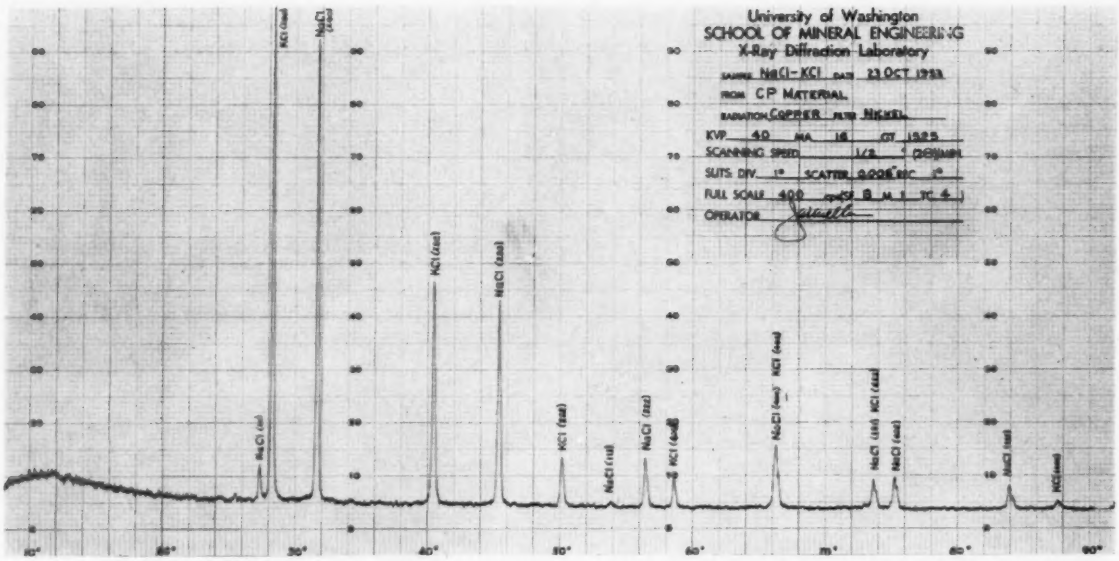


FIG. 3. X-RAY DIFFRACTION PATTERN OF SODIUM CHLORIDE AND POTASSIUM CHLORIDE

based on the fact that each crystal has its own characteristic patterns of *d* spacings and, hence, of the position of the diffraction lines. In addition, the location and types of atoms within the various planes cause the intensity of the diffracted lines to vary. It is then apparent that each crystalline material will have a set location of all its diffraction lines for a given wave length, and that each line will have a given relative intensity. The sample is usually finely ground (—200 mesh) in order that the particles will have a high degree of random orientation.

This randomness is necessary in order to compare patterns of the same material, since preferred orientation would cause the relative intensity of certain lines to be lesser or greater than normal. Figure 3 shows a typical diffraction pattern of a sample containing two unknowns obtained in the Norelco Geiger-counter diffractometer in the X-Ray Diffraction Laboratory of the School of Mineral Engineering. Indexing of this pattern results in the data shown in Table I. A set of index cards has been published by the American Society for Testing Materials which gives the results of various diffractionists on more than 2,500 different crystalline materials. Each material is indexed according to the *d* value of the three most intense lines. Therefore, by selecting the strongest lines of the pattern in Fig. 3 and checking the cards in the ASTM index, we find that the combined patterns from cards of sodium chloride and potassium chloride (Fig. 4) match the lines in Fig. 3.

All samples to be studied may not be in powder form, e.g., metal specimens. The same procedure

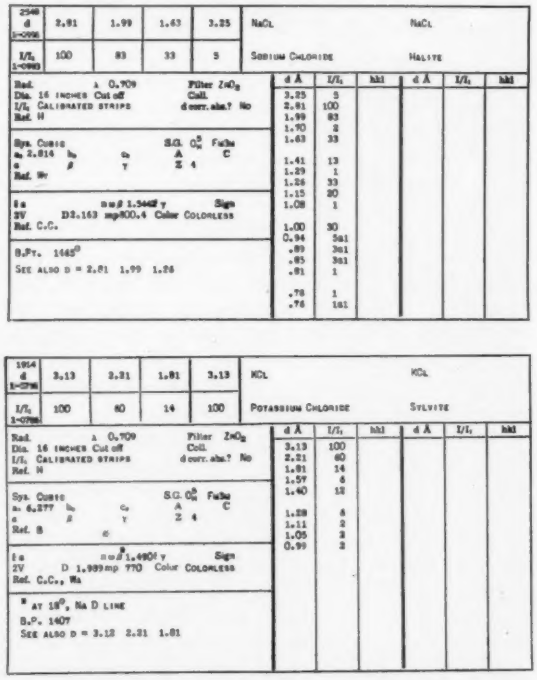


FIG. 4. ASTM INDEX CARDS FOR NaCl AND KCl

may be applied in these cases, but, since the crystals within the metal sample may be preferentially oriented, care must be taken in comparing intensities with those in the ASTM index.

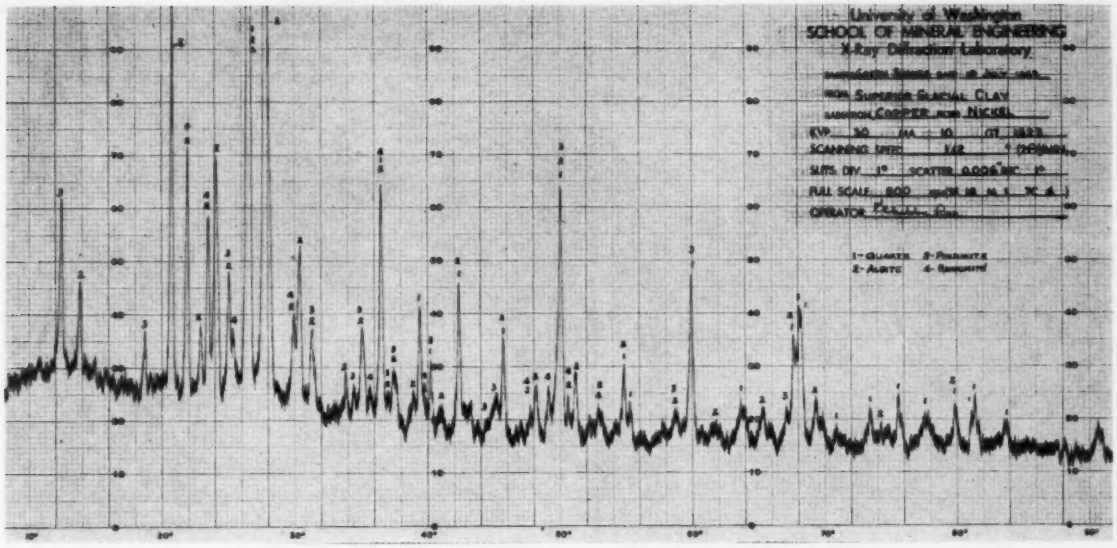


FIG. 5. X-RAY DIFFRACTION PATTERN OF PUGET SOUND GLACIAL CLAY

TABLE I
INDEXING OF X-RAY DIFFRACTION PATTERN
(Figure 3)

OBSERVED DATA			*d*-SPACINGS FROM ASTM INDEX CARDS	
2θ	*d*	*I*	NaCl	KCl
27.3	3.26	7	3.25	....
28.4	3.14	100	....	3.14
31.7	2.82	..	2.81	....
40.5	2.23	48	....	2.21
45.4	1.99	40	1.99	....
50.2	1.82	11	....	1.81
53.8	1.70	1	1.70	....
56.4	1.63	10	1.63	....
58.6	1.57	6	....	1.57
66.3	1.41	13	1.41	1.40
73.6	1.29	5	1.29	1.28
75.3	1.26	6	1.26	....
83.9	1.15	4	1.15	....
87.6	1.12	2	....	1.11

A result of this type of work is shown in Fig. 5, a pattern of a sample of Puget Sound glacial clay obtained by E.C.S. Rao, EES research assistant, in connection with his project (No. 111) on the fundamental properties of this material. This example shows one of the limitations of the method when used alone, i.e., the fact that some patterns contain so many lines that another identification tool must be used to aid in the determination. In this case both polarizing and electron microscopy were utilized.

It should be noted here that one of the chief advantages of qualitative diffraction techniques is the ability to differentiate between isotropic phases present in a sample or to determine, in the case of ceramic reaction, what crystalline phases are present when the reaction is complete.

Quantitative Analysis

Quantitative analysis by X-ray diffraction methods is a very precise procedure, providing the proper instrumentation and techniques are utilized. It is based on the discovery that the intensity of a given line is directly proportional to the concentration of the substance producing the line. This statement somewhat oversimplifies the exact nature of the problem, but, for practical purposes, is true.

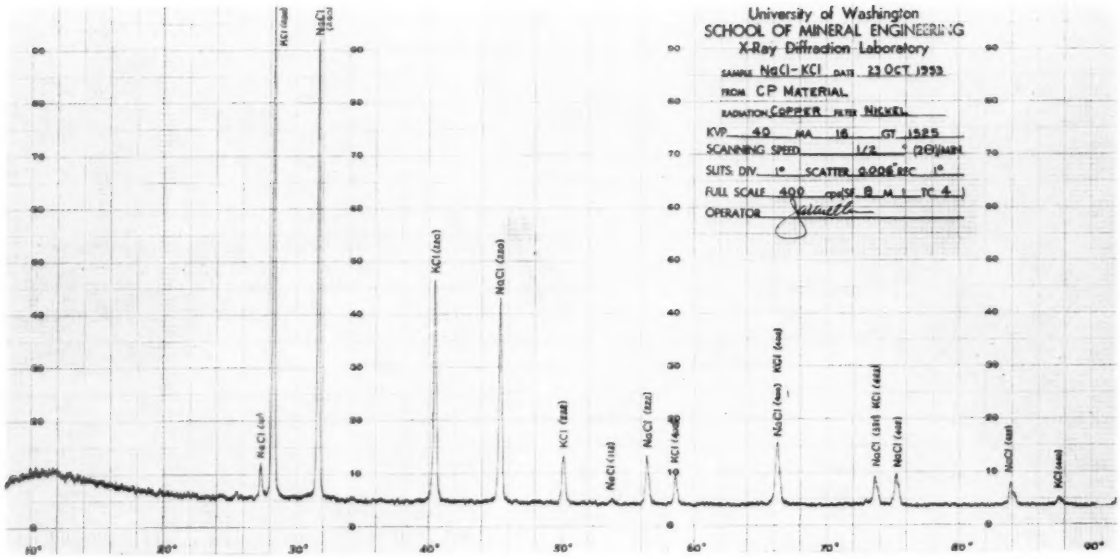
A series of standard curves are prepared by measuring the ratio of the intensity of the line in question for varying concentrations of the substance with a line of an "internal standard" whose concentration is constant. The accuracy of this method involves (1) the use of pure materials for preparation of standards, (2) the use of uniform, finely divided powders, (3) intimate mixing of the components, (4) careful mounting of the specimens, (5) instrument stability and reproducibility of results from day to day, and (6) care in measuring intensities.

Although a great deal of time is sometimes consumed in the preparation of the standard curve, the actual analysis of unknowns, after sample preparation, can be made in a few minutes.

Uses of X-Ray Spectroscopy

Qualitative Analysis

Since von Hevesy's discovery of hafnium by means of X-ray spectroscopy, this analytical tool has been found extremely valuable, owing to the small number of lines in the spectra and the simple relation of line



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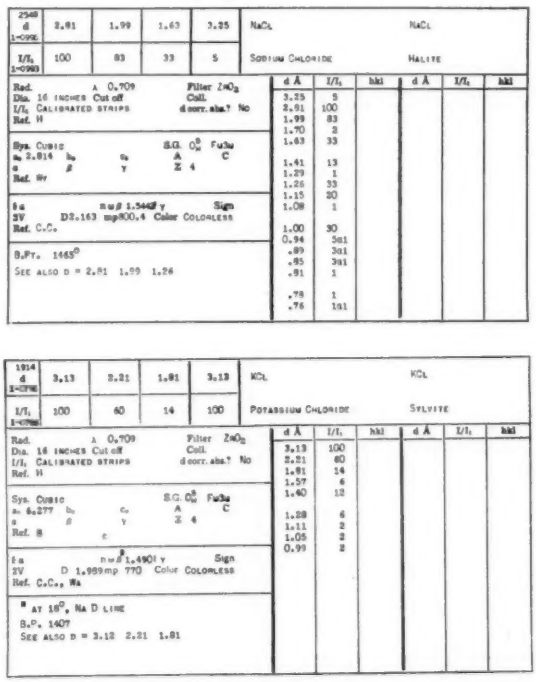

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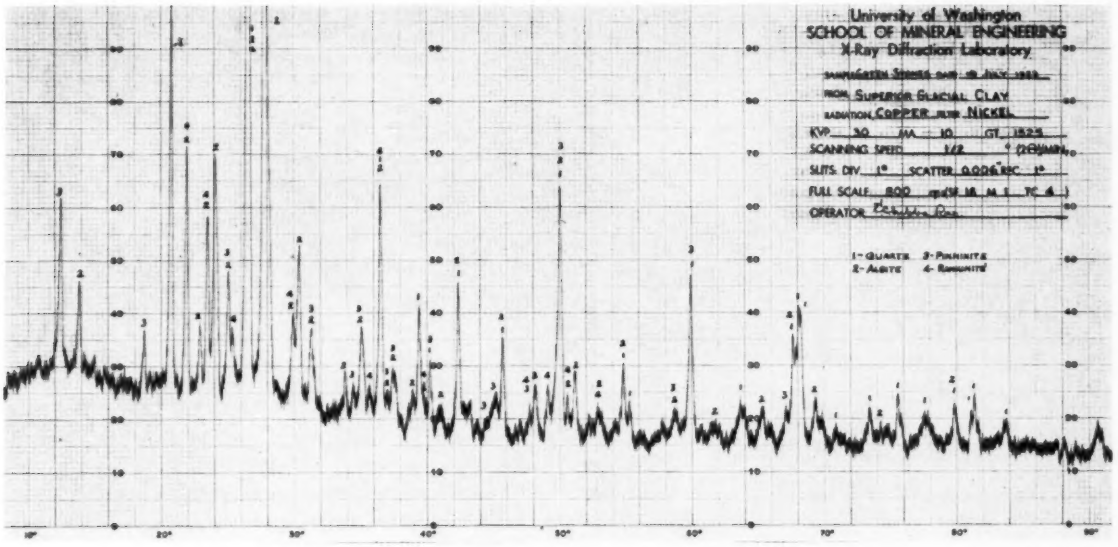

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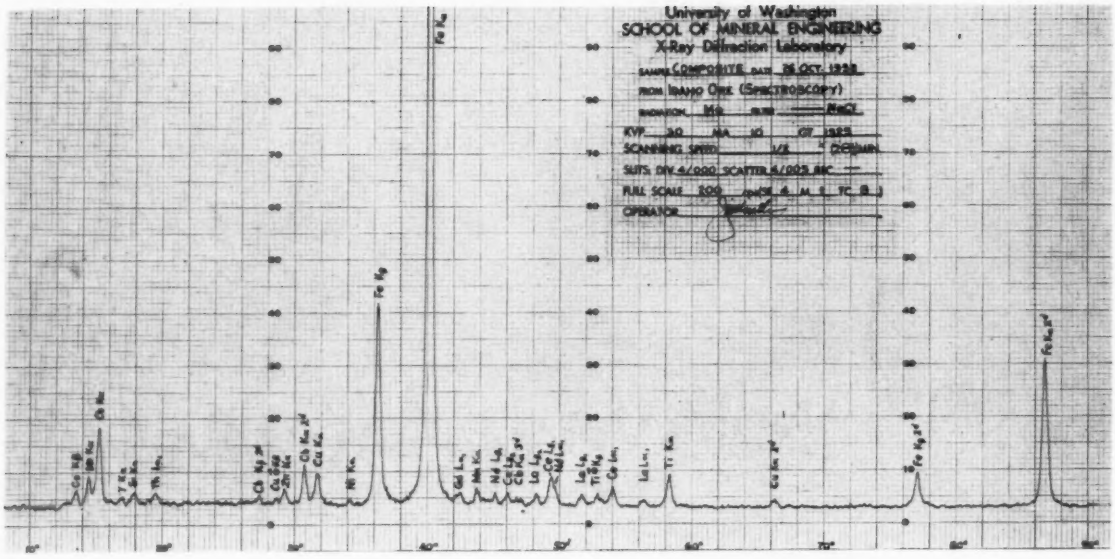

FIG. 6. X-RAY SPECTROGRAPH FOR QUALITATIVE ANALYSIS OF ORE

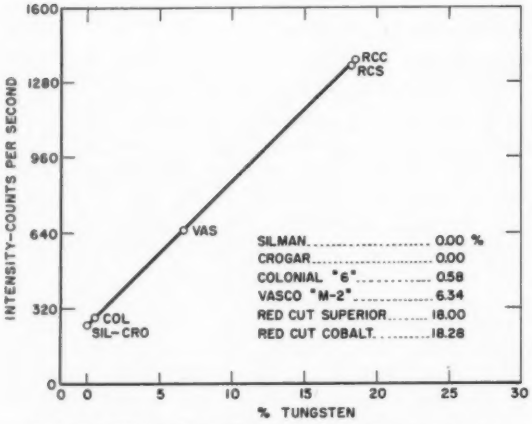

FIG. 7. X-RAY SPECTROGRAPH FOR QUANTITATIVE ANALYSIS OF TUNGSTEN IN TOOL STEEL

intensity to concentration. However, the necessity of using the sample as the target of an X-ray tube and the time involved in photographically recording the spectrum on film have precluded any great use of this method.

With the advent of high-intensity X-ray tubes of the Coolidge type and efficient Geiger-counter spectrometers for accurately detecting and measuring the intensity of diffraction lines, the use of the fluorescent spectrum has become an accepted technique. The qualitative analysis of materials merely requires the operator to calculate the wave lengths of the spectrum obtained from the sample and then determine what materials emit X rays of such wave lengths. This procedure is limited at present, however, to analyzing for elements of atomic number 22 (titanium) and higher, because elements of lower atomic number emit X rays of such long wave lengths that they are absorbed in the air-path between the sample and the Geiger tube.

While routine analyses in metals, ores and chemicals prove valuable, the greatest advantage is obtained in analyzing for those substances which are difficult to identify by other means. For instance, Fig. 6 shows an X-ray spectrograph of an ore sent to the laboratory for analysis which was found to contain iron, manganese, columbium, neodymium, yttrium, cerium, lanthanum, titanium, strontium, thorium, tantalum, and nickel. The lines of molybdenum and copper, which form a constant background, are due to the presence of these elements in the target of the X-ray tube. In these days of great interest in the rare earths and some of the rarer metals, such as tantalum and columbium, this method has proved invaluable to the prospector.

Quantitative Analysis

The nearly linear relationship between concentration and intensity of a given spectral line is affected only by the absorption effects of other materials in the sample. For this reason a series of calibration curves may be necessary for certain analyses if the composition of the material varies. If, however, the composition is fairly constant, the use of a single calibration curve will suffice.

The determination of major constituents of a sample (from a few to 100 per cent) gives X-ray

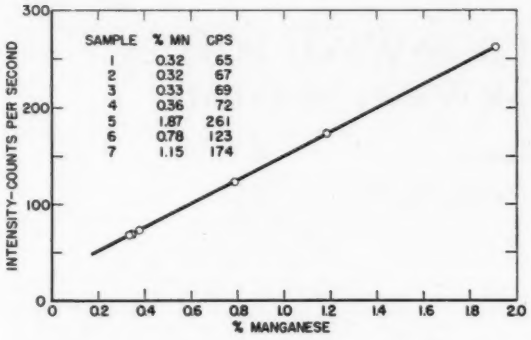

FIG. 8. CALIBRATION CURVE FOR QUANTITATIVE DETERMINATION OF MANGANESE IN CAST STEEL

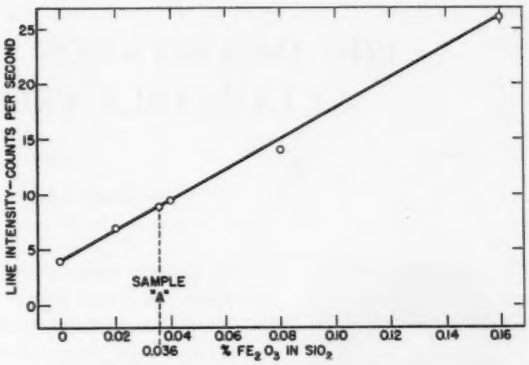

FIG. 9. CALIBRATION CURVE FOR QUANTITATIVE DETERMINATOIN OF IRON IN GLASS SANDS

spectroscopy one of its greatest advantages over optical spectroscopy, since the former can be used to obtain results accurate within a fraction of a percent in a matter of 30 to 60 seconds. Figure 7 shows a calibration curve obtained in the determination of tungsten in tool steels, and Fig. 8 gives a similar curve for the analysis of manganese in cast steel. The latter was prepared by R. T. Torgerson, EES research assistant, for his work on Project No. 139.

The analysis of elements of lower concentration is also possible, although requiring more careful technique and more time. The method of analysis is identical, and the range of this instrumentation available in the School's laboratory makes determination possible down to about 10 parts per million, depending largely, of course, upon the element under consideration and the matrix of the sample.

Figure 9 presents a calibration chart showing the determination of Fe_2O_3 in glass sands. A glass was melted from a batch of which 40 per cent by weight was silica. The molten glass was formed in an appropriate mold and, after cooling, was used as the sample. Although the standard method of reporting iron content in sand is in percentage of Fe_2O_3, the iron content of the glass is of the order of 1 per cent per 100,000. A comparison of the intensity of two lines is shown in Fig. 10. The standard sample is one made up in the laboratory of pure materials with a known amount of Fe_2O_3 added, and the sand sample is one whose iron content was determined by wet analysis.

Figure 11 shows a curve for the determination of nickel in raw ores. This curve was obtained by comparing the intensity with the average of a number of wet analyses on the various samples. The deviation from the average here was about 0.1 per cent, as compared to a 2 per cent deviation from the average by other methods of analysis.

(Continued on page 28)

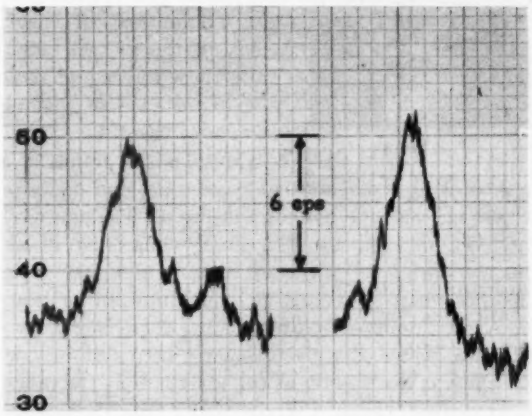

FIG. 10. PATTERN SHOWING COMPARATIVE INTENSITY OF X-RAY (FLUORESCENT) SPECTRAL LINES OF IRON IN SAND SAMPLE *(left)* AND STANDARD SAMPLE
Sand Sample: 0.0085% Fe_2O_3
Standard Sample: 0.010% Fe_2O_3

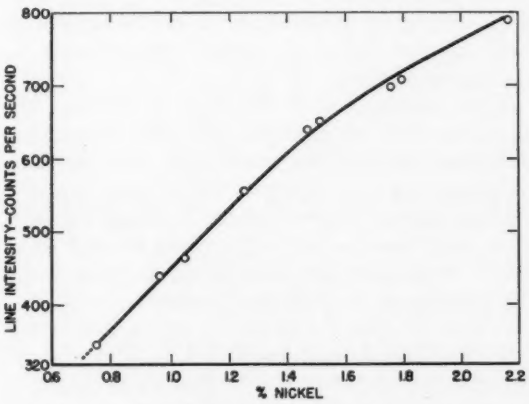

FIG. 11. X-RAY SPECTROGRAPH FOR QUANTITATIVE ANALYSIS OF NICKEL IN ORE

THE IMPORTANCE OF CROSSWIND FORCES ATTAINABLE FROM MOVING SYSTEMS

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Professor of Aeronautical Engineering

F. S. Eastman

Any moving wing system, including the screw propeller, can create crosswind forces that offer important advantages over those obtained simply by inclining the plane of wing motion. An adaptation of blade element theory will illustrate these forces and show the importance of making full use of them.

Consider the action of a pair of wing segments that have equal and opposite crosswind velocity, as shown in Fig. 1. The pair may represent a segment of a single wing, first at an instant during its downward motion, and later at an instant when it attains an equal upward motion; or it may represent corresponding segments of two identical wings of a given moving wing system, one of which is descending at the instant that the other is ascending. Thus, a study of the forces acting on the pair can be used to illustrate the average force acting on a segment of a propeller blade at two instants, one a half-revolution later than the other; or it can be used to illustrate instantaneous forces acting simultaneously on corresponding segments of a contrarotating propeller; or it can be applied to very different types of moving wing systems including bird flight.

Local disturbance of the fluid approaching the segments will be neglected for this illustration. Therefore, the relative velocity, v_b, has the same magnitude for both segments, the advance velocity, v_a, is the same for both, and the crosswind velocity, v_c, is equal but opposite. The mean lift and mean thrust of the pair can be expressed in terms of the lift and drag of the individual segments:

$$L=\frac{v_a}{v_b}\left(\frac{L_d+L_a}{2}\right)+\frac{v_c}{v_b}\left(\frac{D_d-D_a}{2}\right), \qquad (1)$$

$$T=\frac{v_a}{v_b}\left(\frac{L_d-L_a}{2}\right)-\frac{v_c}{v_b}\left(\frac{D_d+D_a}{2}\right). \qquad (2)$$

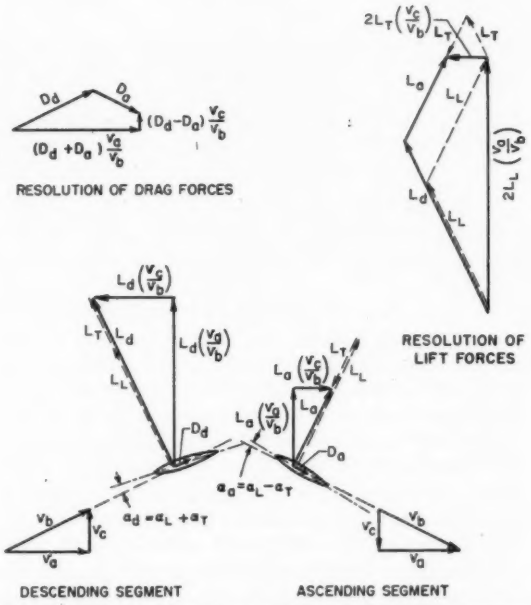

FIG. 1. FORCES ACTING ON A PAIR OF WING SEGMENTS

Since the drag terms are relatively small, lift depends mainly on the mean segment lift, L_L, and thrust depends mainly on the difference in segment lift, L_T, as follows:

$$L_L=\frac{L_d+L_a}{2}, \qquad (3)$$

$$L_T=\frac{L_d-L_a}{2}, \qquad (4)$$

$$L_d=L_L+L_T, \qquad (5)$$

$$L_a=L_L-L_T. \qquad (6)$$

Independent control of lift and of thrust is possible with two controls. One will increase or decrease the angle of attack of both segments equally. The other will increase or decrease their angle of attack differentially. The former will control L_L, and the latter will control L_T. These important components of individual segment lift are illustrated by the dotted arrows in Fig. 1.

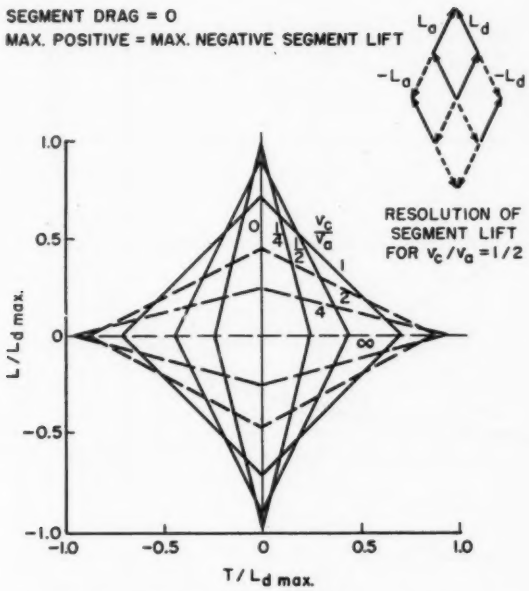

FIG. 2. LIMITS OF ATTAINABLE LIFT AND THRUST AT DIFFERENT RATIOS v_c/v_a

The diamond-shaped areas in Fig. 2 outline the values of lift and thrust attainab e when maximum positive segment lift equals maximum negative segment lift. Boundaries of these areas are obtained by assuming $D_d = D_a = 0$ in Eq (1) and (2), and allowing first L_d and then L_a to vary from maximum positive to maximum negative lift while maintaining maximum lift on the other segment. It is important to observe that, when the crosswind velocity equals the advance velocity, $v_c/v_a = 1$ and equal values of lift and thrust are attainable, but that smaller values of v_c/v_a favor lift, and larger values favor thrust.

Since the active portion of the blades of a high-pitch screw propeller operates near $v_c/v_a = 1$, a control mechanism could be designed that would enable each pair of blade segments to create a crosswind force as large as its thrust. Such a mechanism has been developed for the helicopter but, owing to the very high values of v_c/v_a that are used, the relatively small crosswind forces are obscured by the effect of tilting the rotor. If a moving wing system employing very small values of v_c/v_a can be developed, it is possible that wing surfaces, moving in a way that will produce the needed thrust, can create the much larger crosswind force that is required for lift. Bird flight provides the most common illustration of such a moving wing system, but possibly the conventional screw propeller can be

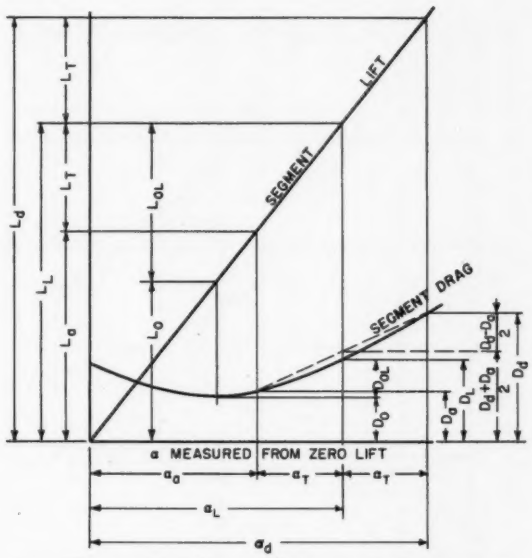

FIG. 3. LIFT AND DRAG FOR THE PAIR OBTAINED FROM SEGMENT LIFT AND DRAG CURVES

altered so that it will gain most of the attainable advantages without adding to the losses that normally arise in the production of thrust.

The influence of segment drag will be illustrated by assuming that the increase in drag with lift is proportional to the square of the change in lift. Letting M be the proportionality factor, using the notation shown in Fig. 3, and expressing all forces in terms of minimum drag, D_0, gives the following expressions for segment drag:

$$\frac{D_d}{D_0} = \frac{D_0}{D_0} + M\left(\frac{L_d - L_0}{D_0}\right)^2 = 1 + M\left(\frac{L_{0L} + L_T}{D_0}\right)^2, \quad (7)$$

$$\frac{D_a}{D_0} = \frac{D_0}{D_0} + M\left(\frac{L_a - L_0}{D_0}\right)^2 = 1 + M\left(\frac{L_{0L} - L_T}{D_0}\right)^2, \quad (8)$$

$$\frac{D_d + D_a}{2} = D_0\left[1 + M\left(\frac{L_{0L}}{D_0}\right)^2 + M\left(\frac{L_T}{D_0}\right)^2\right], \quad (9)$$

$$\frac{D_d - D_a}{2} = \frac{2M\, L_{0L}\, L_T}{D_0}. \quad (10)$$

Substituting Eq (3), (4), (9), (10) in (1) and (2),

$$L = \frac{v_a}{v_b} L_L + \frac{v_c}{v_b} \frac{2M\, L_{0L}\, L_T}{D_0}, \quad (11)$$

$$T = \frac{v_c}{v_b} L_T - \frac{v_a}{v_b} D_0\left[1 + M\left(\frac{L_{0L}}{D_0}\right)^2 + M\left(\frac{L_T}{D_0}\right)^2\right]. \quad (12)$$

The parabola used in Fig. 3 to approximate the actual variation of drag with lift is determined by the value of M. By definition,

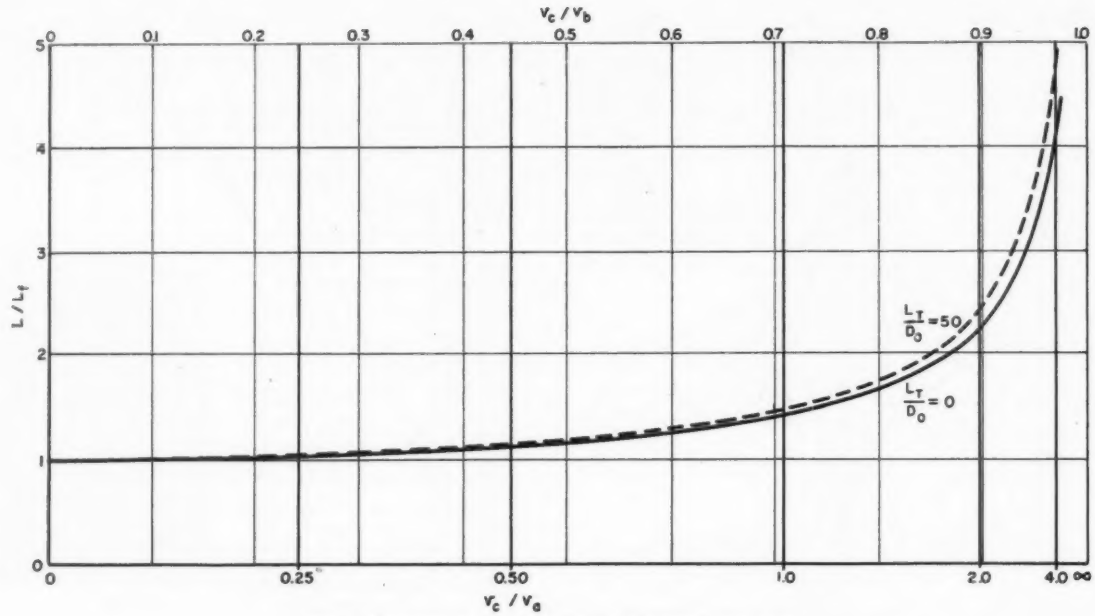

FIG. 4. INFLUENCE OF CROSSWIND VELOCITY ON LIFT
From Eq (14), using $M=0.0004$ and $L_{0L}/L_L=1$.

$$M=\frac{D_{0L}/D_0}{(L_{0L}/D_0)^2}=\frac{D_{0L}\,D_0}{{L_{0L}}^2}.$$

In terms of wing-section coefficients this ratio is $\frac{dC_D}{dC_L{}^2}\,C_{D0}$, for which $0.05\times 0.008=0.0004$ is sufficiently representative to be used for the illustrations that follow.

The ratio of the lift of the pair to fixed wing lift is of interest because it shows the gain in lift due to crosswind velocity. When the wing motion is stopped, $v_c=0$ in Fig. 1, and the fixed-wing condition is represented. In this special case, v_b is reduced to v_a and fixed-wing lift can be written

$$L_f=\left(\frac{v_a}{v_b}\right)^2 L_L. \qquad (13)$$

When used with Eq (11), this gives

$$\frac{L}{L_f}=\frac{v_b}{v_a}\left(1+\frac{v_c}{v_a}\,2M\,\frac{L_{0L}}{L_L}\,\frac{L_T}{D_0}\right). \qquad (14)$$

The solid line in Fig. 4 is a plot of this expression with $L_T=0$, so that the influence of the drag term is eliminated. The dotted line is indicative of the maximum influence of the drag term, because the assumed values, $L_{0L}/L_L=1$ and $L_T/D_0=50$, are larger than those to be expected. Apparently the influence of blade drag may cause an appreciable increase in lift when the crosswind velocity is high, relative to the advance velocity. However, the increase is small throughout the important range $(v_c/v_a)<2$, and will be neglected for the sake of simplicity.

The ratio of the thrust of the pair to the fixed-wing value of minimum drag will be used to illustrate the variation in thrust with crosswind velocity. When the wing motion is stopped, segment drag becomes the fixed-wing value,

$$D_f=\left(\frac{v_a}{v_b}\right)^2 D_L \quad \text{and} \quad D_{0f}=\left(\frac{v_a}{v_b}\right)^2 D_0. \qquad (15)$$

The ratio of thrust to D_{0f} is obtained from Eq (15) and (12):

$$\frac{T}{D_{0f}}=\frac{v_b}{v_a}\left[\frac{v_c}{v_a}\,\frac{L_T}{D_0}-1-M\left(\frac{L_{0L}}{D_0}\right)^2-M\left(\frac{L_T}{D_0}\right)^2\right]. \qquad (16)$$

The solid line curves in Fig. 5 are plots of Eq (16) illustrating the special case when $L_{0L}=0$. The dotted curves show the effect of operating at a higher angle of attack, so that $L_{0L}/D_0=50$. The pair overcomes its own drag when $T=0$, and it is important to note that this condition requires very little crosswind velocity. Even when L_T is only about 1/15 of maximum segment lift (see curve for $L_T/D_0=10$), the pair overcomes its own drag when the crosswind velocity is little more than 1/10 of the advance velocity. Birds employ a relatively slow wing motion while in steady horizontal flight.

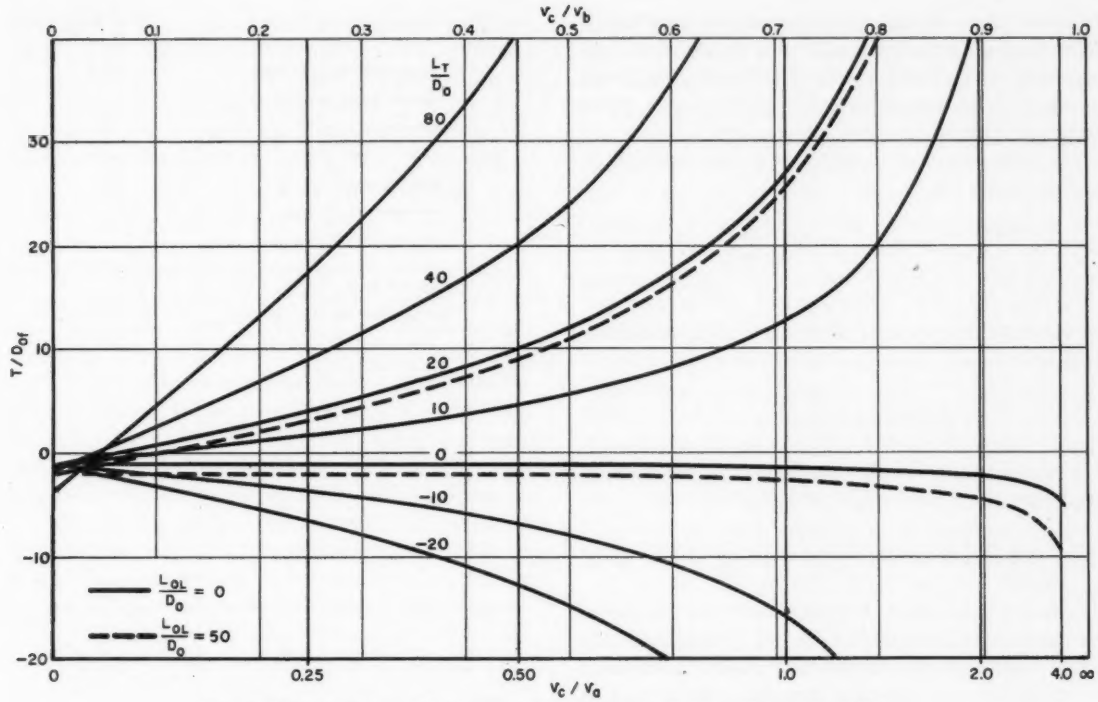

FIG. 5. INFLUENCE OF CROSSWIND VELOCITY ON THRUST [FROM EQ (16)]

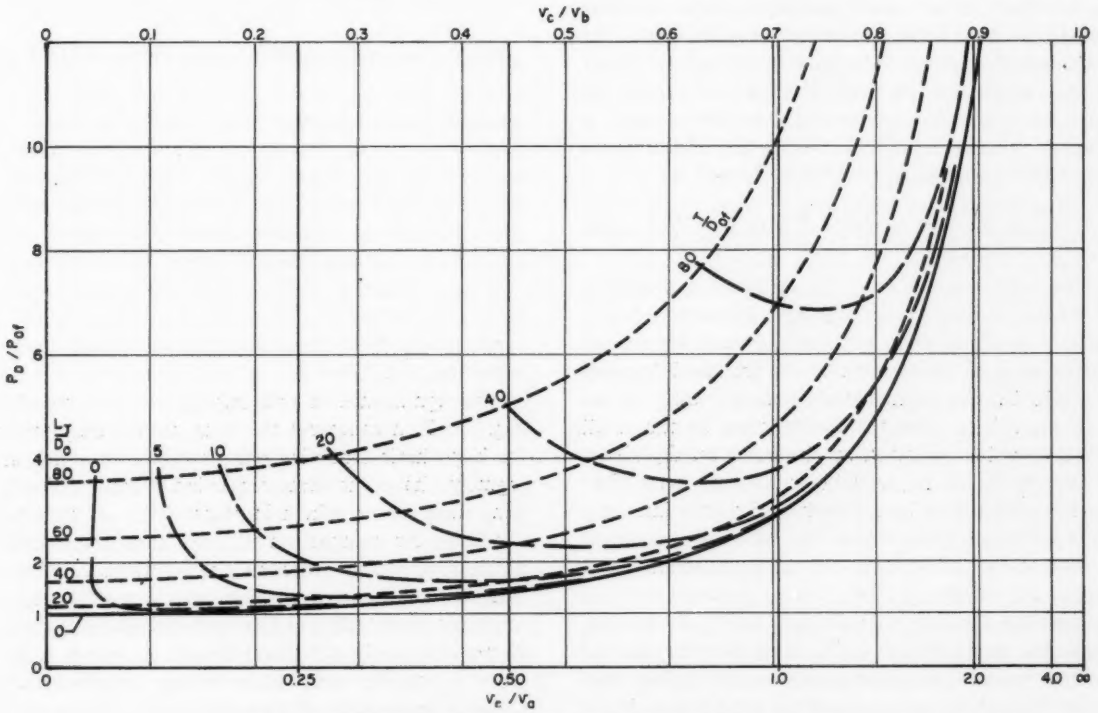

FIG. 6. INFLUENCE OF CROSSWIND VELOCITY ON DRAG POWER

From Eq (20) with $L_{0L}=0$ and $M_T=0.0004$.

Probably they instinctively choose the method of flight that requires minimum propulsive effort. At any rate, the following study of segment drag power shows that minimum power for horizontal flight occurs at remarkably small values of v_c/v_a.

The mean segment drag power of the pair will be written, using Eq (9), as

$$P_D = v_b\left(\frac{D_d+D_a}{2}\right) = v_b\, D_0\left[1+M\left(\frac{L_{0L}}{D_0}\right)^2+M\left(\frac{L_T}{D_0}\right)^2\right]. \tag{17}$$

Power required to overcome fixed-wing minimum drag is

$$P_{0f} = v_a\, D_{0f} = \frac{v_a^3}{v_b^2}\, D_0\,. \tag{18}$$

Therefore, the ratio of drag power of the pair to fixed-wing minimum drag power is

$$\frac{P_D}{P_{0f}} = \left(\frac{v_b}{v_a}\right)^3\left[1+M\left(\frac{L_{0L}}{D_0}\right)^2+M\left(\frac{L_T}{D_0}\right)^2\right]. \tag{19}$$

It may be possible to introduce periodic changes in the drag curve illustrated in Fig. 3 so that $(D_d+D_a)/2 = D_L$, and L_T causes no change in drag. Birds may be able to do this because they have some control over the camber of their wings. A rigid wing with a spanwise hinge could accomplish the purpose nearly as well if the periodic change is small. At any rate, it appears to be possible to reduce, if not eliminate, the increase in drag with L_T. To represent such a condition the value of M should be reduced in the last term of Eq (19) but not in the middle term. Therefore two different values of M will be used:

$$\frac{P_D}{P_{0f}} = \left(\frac{v_b}{v_a}\right)^3\left[1+M_L\left(\frac{L_{0L}}{D_0}\right)^2+M_T\left(\frac{L_T}{D_0}\right)^2\right]. \tag{20}$$

The solid line curve in Fig. 6 shows the increase in minimum drag power as v_c/v_a is increased. It is a plot of Eq (20) when both the lift and the thrust terms are zero. Some lift may be produced, because L_L will be the segment lift corresponding to its minimum drag. But the thrust must be the small negative value indicated by the curve for $L_T/D_0=0$ in Fig. 5, unless M_T can be reduced to zero. The dotted curves have been drawn to show the influence of the thrust term when $M_T=0.0004$, but they represent the influence of the lift term equally well when $M_L=0.0004$. The broken lines have been added with the aid of a plot such as Fig. 5, to illustrate the variation of T/D_{0f} corresponding to the dotted curves. Minimum points on the broken lines move to the left and approach the solid line as M_T is

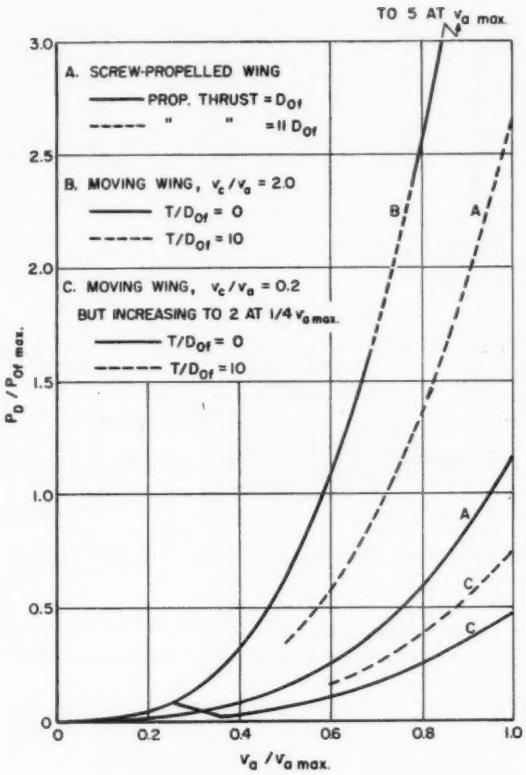

FIG. 7. COMPARISON OF WING DRAG POWER IN FLIGHT

reduced, but, neglecting the possibility of such reduction, the curve for $T/D_{0f}=0$ shows that power required to overcome segment drag reaches its minimum value when v_c/v_a is less than 0.25. Even when T/D_{0f} is increased from 0 to 40, so that thrust may have a magnitude comparable with that normally required of lift, minimum power occurs when v_c/v_a is less than one. Yet the moving wing systems employed for aircraft operate mainly in the region beyond $v_c/v_a=2$.

The significance of this information is shown by Fig. 7, which compares the wing profile drag power for hypothetical moving wing systems in which all segments have the same crosswind velocity. Fixed-wing drag power, which increases with v_a^3, provides the basis for comparison. Curve A represents the power required to overcome the profile drag of this wing by means of a conventional propeller which contributes an additional power loss assumed to be 15 per cent of the wing drag power. Curve B represents a moving wing system that operates with $v_c/v_a=2$, regardless of forward speed. If its total

wing area is the same as that of the fixed wing, its minimum wing drag power would be increased in the ratio $(v_b/v_a)^3$ according to Eq(20), but its lift would be increased in the ratio v_b/v_a according to Eq (14). Therefore, it is assumed that wing area will be reduced in proportion to the ratio of lift, $L_f/L=v_a/v_b=1/2.236$ when $v_c/v_a=2$. Consequently, profile drag power computed from the ratio $(1/2.236)\,(v_b/v_a)^3$, is 5 times that for the fixed wing. Curve C represents a moving wing system that operates with $v_c/v_a=2$ at speeds up to $\frac{1}{4}\,v_a$ max, but, at speeds beyond that for which increased lift is needed, it operates with $v_c/v_a=0.2$. This enables the same reduction in wing area as was assumed for Curve B, and the wing drag power is the same for speeds up to $\frac{1}{4}\,v_a$ max. The transition from $v_c/v_a=2$ to 0.2 is made by using gradually diminishing values of v_c/v_a as the speed increases, so that the increase in lift according to Eq (14) is just enough to provide the same maximum lift as that at $\frac{1}{4}\,v_a$ max. At speeds beyond the transition, v_c/v_a can be reduced to 0.2, and the drag power, computed from the ratio $(1/2.236)\,(v_b/v_a)^3$, is only 0.475 times that for the fixed wing. Apparently, forward flight can be accomplished with substantially less power than is required for the fixed wing, if optimum use can be made of the thrust and crosswind forces attainable from moving wing systems.

Dotted curves have been added in Fig. 7 to represent the relatively high thrust condition, $T/D_{0f}=10$. Assuming that propeller losses remain 15 per cent of the total thrust power of the screw propeller, they will increase in the ratio of the thrust, $(T+D_{0f})/D_{0f}=11$. Therefore, propeller losses have been increased from 0.15 to 1.65 times that for overcoming wing profile drag. The corresponding increase for Curve B is negligible for this general comparison, because with $v_c/v_a=2$, Fig. 5 shows that $T/D_{0f}=10$ when L_T/D_0 is much less than 10, and when translated to Fig. 6 this condition is represented by a point adjacent to the solid line curve. When v_c/v_a is variable, as assumed for Curve C, minimum P_D/P_{0f} estimated from the curve for $T/D_{0f}=10$ in Fig. 6 is about 1.6, and it occurs when v_c/v_a is approximately 0.45. In this case, therefore, wing drag power is $(1/2.236)\times 1.6$, or 0.73 times the fixed-wing drag power, and it may be possible to reduce it considerably below this figure if M_T can be reduced as suggested previously. Apparently the potential advantage of the moving wing system with variable v_c/v_a, when compared with the screw-propelled fixed-wing, is greater under conditions of high thrust than it is in level flight. This advantage is important for steep climbs and for level flight at speeds less than the stalling speed of the fixed wing. Birds provide striking demonstrations of this fact.

The foregoing analysis illustrates the action of a single pair of wing segments or a group of segments operating under identical conditions. By estimating the single pair that best represents the composite action of all segments, the illustration can be used to judge actual moving wing systems. A true quantitative study, however, requires the summing up of the action of many pairs. The wing action of a bird, for example, can be studied as completely as desired by considering bands of pairs located at different distances from the wing root, each of which is composed of enough individual pairs to represent the changes in crosswind velocity and wing configuration that take place during a complete cycle of wing motion. Similarly, the crosswind forces attainable from a screw-wing (a term used to describe a wing system of the contrarotating propeller type) can be studied by considering several ring-shaped bands of pairs located at different radial distances from the axis. In each band the crosswind force produced by an individual pair located on the horizontal diameter will act in the vertical direction, while that of a pair located on the vertical diameter will act in the horizontal direction, and all others will have components in both directions. By introducing a periodic variation in the blade angle similar to the cyclic pitch control for helicopters, it is possible to control the crosswind forces on all pairs in such a way that the total crosswind force will act in any desired direction. Moreover, it appears to be possible to superimpose such additional periodic changes in blade angle that the thrust of pairs located at opposite ends of the vertical diameter, and of the horizontal diameter, can be controlled differentially, thereby providing positive control of both pitching moment and yawing moment. It has been pointed out that maximum advantage can be gained from crosswind forces when the value of v_c/v_a is very low. Therefore, the wind chords of a screw-wing should be set nearly parallel to the axis of rotation, like a screw propeller designed for a very high advance ratio. This permits the use of large highly tapered wings to satisfy strength and stiffness requirements.

It is important to study the effect of inclining the plane of motion of the pair illustrated in Fig. 1, because an increase in maximum lift is possible that will benefit flight at low forward speed. Also, knowledge of this effect is needed for consideration

of the stability of moving wing systems. For the present illustrative purposes, however, it is sufficient to note that the drag power of the pair increases with the mean value of v_b^3, and consequently its minimum value occurs under the conditions assumed. Small angles of inclination result in some gain in lift with relatively small increase in drag power, but this simply means that the illustration presented here conveys a slightly conservative idea of the optimum characteristics attainable from moving wing systems.

Between the instant when a wing segment acts as the descending, and that when it acts as the ascending segment of a pair, it must undergo a change in velocity, or angle of attack, or both, in order to accomplish the dual purpose of producing thrust and crosswind force. It is important to determine the influence of the resulting unsteady flow condition on the action of the pair. T. C. Lin, while employed as a research engineer at the University of Washington, completed a theoretical study[1] with which this influence can be evaluated in the case of a wing subjected to harmonic crosswind motion. His work shows that the mean lift and thrust are not much affected if the wing chord is less than 1/15 of the wave length of the path, but the instantaneous values of lift are influenced in a manner that may prove to be very important. Apparently an additional periodic force is created by the unsteady flow. Under certain conditions this force directly opposes the inertia force that arises from the wing motion. Perhaps natural flight would be impossible if it did not take advantage of this method of relieving the seemingly intolerable inertia forces. At any rate, delicate insect wings withstand an acceleration of more than 2000 g if the frequency is 200 cycles per second with one-inch stroke, and the relatively heavy wings of a bird withstand an acceleration of more than 240 g if the frequency is 20 cycles per second with one-foot stroke. It seems probable, therefore, that wings with harmonic crosswind motion can be designed so that most of the inertia force is balanced aerodynamically all along the wing. If mechanical difficulties can be satisfactorily solved, this type of motion will provide maximum improvement in forward flight characteristics, because it enables the crosswind force of all pairs to be used most effectively for the creation of the needed lift. The cycloidal type of motion, recommended for many years by the late Professor Emeritus F. K. Kirsten,[2] may offer the best solution to the mechanical difficulties, but all methods of producing periodic crosswind motion need to be considered. The author discussed several alternative moving wing systems in a memorandum[3] issued three years ago regarding the practicability of the cyclogiro type of moving wing system tested in the F. K. Kirsten Aeronautical Laboratory.

(Continued on page 28)

M. I. T.'s Dr. Sherwood Delivers Lectures to Chemical Engineers

Dr. Thomas K. Sherwood

DR. THOMAS K. SHERWOOD, professor of chemical engineering and former dean of engineering at the Massachusetts Institute of Technology, was a visiting lecturer in the Department of Chemical Engineering during the first two weeks of November. Dr. Sherwood, one of the country's outstanding chemical engineers, has been at M.I.T. since 1930. During this period he has authored or co-authored two reference books in chemical engineering and over sixty articles in various technical publications. He has served as consultant to numerous industries and to the U. S. Government and has played an active role in many professional societies such as the A.I.Ch.E. and the A.S.E.E. He is especially well known for his work in engineering education and his studies in the field of mass transfer. His many honors include the William H. Walker Award in chemical engineering and the U. S. Medal for Merit.

During his campus visit, Dr. Sherwood delivered four departmental lectures and conferred with the chemical engineering faculty and graduate students on research topics. "The Mathematical Treatment and Mistreatment of Data" discussed various methods used to correlate data in chemical engineering problems, especially problems where large numbers of varables were suggested; and certain potential dangers for their misue were pointed out.

The remaining three lectures, "The Relation Between Mass Transfer and Fluid Friction in Turbulent Flow," "Basic Concepts in Mass Transfer," and "Barriers to Mass Transfer," formed an integrated series in Dr. Sherwood's field of specialization. Recent concepts of fundamental theory were reviewed for mass transfer between phases in turbulent motion with emphasis on the close relationship between this type of transfer and heat and momentum transfer under similar conditions.

In addition to lecturing before the Chemical Engineering Department, Dr. Sherwood presented addresses before the local sections of the A.I.Ch.E. and the A.C.S. and before the Vancouver Chemical Engineering division of the C.I.C.

THERMODYNAMIC PROPERTIES OF ANILINE*

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Although aniline has long been known as a chemical especially useful as a base for dyes, only during recent years has it been investigated as a fuel.[1,2,3] To facilitate further study of aniline in this direction, available thermodynamic data have been collected, and, by methods of extrapolation and interpolation, the properties of pressure, volume, temperature, enthalpy, and entropy have been estimated in the gas and liquid phases of aniline between 20° F and 2000° F and at pressures up to 10,000 psia.

Critical Constants and Phase Change Points

The critical pressure and temperature of aniline were experimentally determined by Guye and Mallet[4] as 769 psia and 797.8° F. These values have been quoted, and presumably accepted, by the editors of the *International Critical Tables*,[5] by Kobe and Lynn,[6] and by R. R. Dreisbach.[7] In the present work the critical temperature and pressure were estimated by Meissner's method[8] which indicated values[9] within 1¼ per cent and 3 per cent, respectively, of those determined by Guye and Mallet.

The triple point among gas, liquid, and solid phases was located at 19.2° F by A. G. Chowdri and F. C. Auluck of the University of New Delhi.[10] The normal boiling point reported by a number of investigators is as follows: 363.90–94° F,[11] 363.78–90° F,[12] 363.9° F,[13] 363.07° F,[14] 363.74° F,[15] and 363.92° F.[16] The value 363.9° F is accepted for this work. The normal freezing point has also been determined several times as follows: 20.7° F,[17] 20.8° F,[12] and 21.0° F.[16] Parks, Huffman, and Barmore's value of 20.7° F is the most widely accepted of these.

J. L. McCarthy

No direct measurements seem to have been made of the critical volume. Since the rate of change of volume with temperature becomes immense near the critical point, this constant is best determined not by experimental methods but by the use of the Cailletet-Mathias law of rectilinear diameters. Applying this method, Guye and Mallet[4] arrived at the value 0.0471 ft³/lb. Dreisbach's equation for the Cailletet-Mathias rectilinear diameter[7] yields the value, 0.0472 ft³/lb. The writers, using available experimental data, have written the following equation for this line:

$$\rho_l + \rho_g = 65.90 - 0.0303T, \qquad (1)$$

where ρ_l and ρ_g represent the density in liquid and gaseous phase, respectively. Solution of Eq (1) at the critical temperature gives the critical volume as 0.0473 ft³/lb. Meissner's method yielded the value 0.0502 ft³/lb.[9] Dreisbach's value of 0.0472 ft³/lb is accepted for the present work.

Pressure, Volume, and Temperature Relationships

Saturated Vapor and Saturated Liquid

The first step in the evaluation of pressure, volume, and temperature data was that of determining the properties of the saturated vapor and liquid by initially determining the vapor pressure-temperature relationship. From data of a number of experimenters,[4,13,14,20] a logarithm vapor-pressure versus reciprocal-temperature graph was made on a large scale.[9] Two empirical expressions by Dreisbach[7] were plotted along with these data and found to give results within 10 per cent of experimental values.

These data are represented here with the following three linear equations:[9]

*Condensed from the thesis of John H. Lienhard, Jr., submitted for the degree of M.S. in Mechanical Engineering. The project, E.E.S. No. 150, was supervised by Dr. McCarthy, under whose direction the thesis was prepared, and Professor Nordquist.

from 540° F to the critical point:

$$\log_{10} P = 5.9088 - 3813/T, \quad (2)$$

from 180° F to 540° F:

$$\log_{10} P = 6.5141 - 4409.2/T, \quad (3)$$

from 19° F to 180° F:

$$\log_{10} P = 8.1660 - 5469/T, \quad (4)$$

where P = psia, and T = °R. In general these equations represent the measured pressures within about 2 per cent except between about 150 to 200° F. In this range Eq (3) and (4) yield values which may be as much as 8 per cent high. The rather sharp curve of the vapor-pressure line in this range tends to make the straight line approximations less accurate.

Saturated liquid and vapor data were now completed with the addition of volumes over the temperature range 19° F to 798° F. Saturated liquid density up to 200° F was determined from an equation for liquid density as a function of temperature, given in the *International Critical Tables*,[5] and based upon Tyrer's data.[19] Use of this equation was permissible, even though the expression was meant to apply at atmospheric pressure, since the vapor pressures are subatmospheric in the temperature range of interest. Density at these lower pressures will not vary significantly from values at one atmosphere. The reciprocal of these densities yielded the desired volume data.

Saturated vapor volumes from 19° F to 200° F were estimated by the ideal gas law, inasmuch as no significant deviation from ideal behavior should exist here where the vapor pressure at 200° F is about 0.67 psia. Gurevich and Sigalovskaya have given experimental values for aniline vapor densities at 32° F and 122° F[20] which lie roughly within 1 per cent of ideality. It appears likely that the discrepancy here represents experimental error and that the gas is virtually ideal.

From 200° F to the critical point, the saturated liquid and vapor volumes were calculated together, with the use of Eq (1). The vapor density was first estimated by use of generalized compressibility charts,[21,22,23] and in the present work Obert's chart[24] was used. Liquid density was estimated[9] by substitution of the vapor density in Eq (1).

The data for saturated aniline are thought to be correct within 2 per cent from the boiling point to 750° F, and within 5 per cent from here to the critical point.[9] Below 364° F, 1 per cent accuracy can be claimed, based upon the following spot check at the normal boiling point by use of the Clausius-Clapeyron equation:

$$dP/dT = \Delta H_v/T\Delta V. \quad (5)$$

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The rate of change of vapor pressure with boiling point, dP/dT, has been experimentally determined by a number of investigators,[11,16,25] Timmermans' value[11] of 19.6 mm Hg/°C being representative; normal latent heat of vaporization (ΔH_v) has been reported by Louguinine,[26] Awbery and Griffiths,[27] and Marshall.[28] Miss Marshall's value of 113 cal/gm is the most widely accepted; the volume change on vaporization, ΔV, calculated from these numbers was 6.30 ft³/lb, a result in good agreement with the volume change of 6.28 ft³/lb computed by use of the generalized compressibility factors.

To aid in the interpolation of saturated vapor data below 350° F, the following two equations were developed[9] by combining the ideal gas law with Eq (3) and (4):

$$\text{Below } 180^\circ \text{ F:} \quad \rho_g = \frac{1.2729\ (10)^3}{T\, e^{12.593/T}}; \quad (6)$$

$$180^\circ \text{ F to } 350^\circ \text{ F:} \quad \rho_g = \frac{2.8367\ (10)^7}{T\, e^{10.183/T}}. \quad (7)$$

A logarithm–P versus reciprocal–temperature plot[9] provided this additional value:

$$305^\circ \text{ F to } 570^\circ \text{ F:} \quad \log_{10} \rho_g = 4.108 - 4032.3/T. \quad (8)$$

Equation (6) is believed to give density values accurate within roughly 1 per cent at temperatures below 150° F. Equation (7) is accurate to about 1 per cent above, and to about 3 per cent below 400° F.

The pressure, volume, and temperature relations for saturated aniline are given in Table I.

Superheated Gas

No experimental data could be found for gaseous aniline. Thus pressure-volume-temperature relations were estimated entirely by use of generalized compressibility factors. Results are included in Table II. Pressure-volume-temperature relations were also estimated[9] by using the Beattie-Bridgman equation of state with constants evaluated by the generalized method of Maron and Turnbull,[29] to give the following statement:

$$P = \frac{.08026}{V^2}\left[1 - \frac{2.562\ (10)^7}{VT^3}\right]\left[V + .334\left(1 - \frac{.231}{V}\right)\right] - \frac{36.75}{V^2}\left[1 - \frac{.2278}{V}\right], \quad (9)$$

where: P=atmospheres, V=liters/gm-mole, and T=°K. This expression was checked at representative points and found to agree with generalized compressibility values within about 1 per cent. Near the critical point, however, accuracy became exceedingly poor. On the 798° F isotherm, for example, a 1 per cent disagreement existed up to 600 psia, then rapidly increased to 90 per cent at the critical pressure.

Subcooled Liquid

Density of liquid aniline was estimated[9] by use of Watson's expansion factors.[30] At low pressures these values were checked at some points with the previously mentioned liquid density expression[5] and with data given by Gibson and Loeffler.[31] Certain other properties of liquid aniline have been reported: viscosity,[5,32] sonic velocity,[32-39] and surface tension.[32,40,41,42]

Enthalpy and Entropy of Vaporization

The latent heat or enthalpy of vaporization was estimated[9] by Watson's latent heat equation,

$$\Delta H_v = \Delta H_v^\circ \, (1 - T/T_c)^{\text{exp}}, \qquad (10)$$

the constants for which have been determined by Dreisbach[7] as follows:

$$\Delta H_v = 194.1 \, (1 - T/699)^{.5075}. \qquad (10a)$$

The Clausius-Clapeyron equation was used to check results from this expression over the range of temperatures from 19° F to 798° F. Use of the Clausius-Clapeyron equation, however, required dP/dT values. Dreisbach has presented the following equation for dP/dT as a function of vapor pressure:

$$dP/dT = .001374 \, (7.24179 - \log_{10} P)^2. \qquad (11)$$

Values of dP/dT, obtained by differentiation of Eq (2), (3), and (4), ranged from about 15 per cent low to 20 per cent high when compared with the results from use of Dreisbach's equation.[9] This wide variation was expected, since Eq (2), (3), and (4) are only straight line approximations of a curve and thus will slope too much at the high temperatures and too little at the low temperatures. One value of dP/dT, available from an experiment by Timmermans[11] made at atmospheric pressure, agreed within 1½ per cent that obtained by use of Eq (11). Considering these factors, the best estimate of dP/dT was taken to be that given by Eq (11), and these values, together with volumes appropriate for saturated liquid and vapor phases as shown in Table I, were used to estimate enthalpy of vaporization.[9]

When the results obtained by use of Watson's equation were compared[9] with those obtained by the Clausius-Clapeyron equation, the maximum variation proved to be about 4 per cent up to 650° F. Equation (10a) gives a value of 203.5 Btu/lb at one atmosphere, which agrees with the value obtained experimentally by Marshall.[28]

Entropies of vaporization, ΔS_v, were computed from the enthalpies of vaporization by the relationship,

$$\Delta S_v = \Delta H_v / T. \qquad (12)$$

Results are shown in Table I.

Enthalpy

The enthalpy of aniline has been arbitrarily fixed at zero for the standard reference state taken as the saturated liquid at the triple point, i.e., at a standard state temperature, T_0, of 19° F[10] and a standard state pressure, P_0, of 0.000592 psia or 0.001206 in. of Hg, from Eq (4). For any other state, the enthalpy can be calculated by use of the equation:

$$H = \Delta H_{v0} + \int_{T_0}^{T} C_{p0} \, dT + \int_{P_0}^{P} V - T \left| \frac{\partial V}{\partial T} \right|_p dP, \qquad (13)$$

where the first term, ΔH_{v0}, is the enthalpy of vaporization at the standard state pressure and is found by Eq (10a) to be 273 Btu/lb; the first integral gives the enthalpy of aniline at a particular temperature, but at a sufficiently low pressure so that its behavior is substantially that of an ideal gas; and the second integral adds the enthalpy contribution arising from increase in pressure above the region of ideal gas behavior.

To evaluate the first integral, values for the specific heat at low pressure, C_{p0}, in the gas phase are needed. For the temperature range of present interest, no experimental data seem to have been published. The necessary specific heat values have therefore been estimated by two separate methods: by use of generalized bond frequencies,[43] and by considering contributions of specific chemical groups to specific heat.[9,44] The results of the two methods agree with each other within about 3 per cent over practically all of the temperature range of interest. Results from the former are thought to be the more accurate and have been accepted for this work. The actual integration of the first integral was performed graphically upon a plot of C_{p0} versus temperature.[9]

The second integral could be evaluated by performing the indicated differentiation and integrations graphically; however, accuracy of such a

TABLE I

Saturated Vapor and Liquid Aniline

Temp. °F	Pressure Psia	Volume (ft^3/lb)			Enthalpy (Btu/lb)			Entropy (Btu/lb-°R)		
		V_l	ΔV_v	V_g	H_l	ΔH_v	H_g	S_l	ΔS_v	S_g
20	.000592	.01532	93,500	93,500	0	273	273	0	.569	.569
30	.00101	.01542	55,900	55,900	5	272	277	.007	.555	.562
40	.00170	.01547	33,900	33,900	9	270	279	.015	.540	.555
50	.00275	.01554	21,400	21,400	13	268	281	.025	.525	.550
60	.00444	.01561	13,500	13,500	17	266.5	283.5	.031	.513	.544
70	.00684	.01569	8,940	8,940	21.5	264.5	286	.040	.499	.539
80	.0108	.01576	5,780	5,780	25.5	263	288.5	.047	.487	.534
90	.0165	.01582	3,830	3,830	30	261	291	.054	.475	.529
100	.0248	.01589	2,580	2,580	35.5	258	293.5	.064	.461	.525
120	.0547	.01606	1,200	1,200	45	255	300	.079	.440	.519
140	.1125	.01620	615	615	55	251	306	.095	.418	.513
160	.200	.01638	325	325	63.5	247.5	311	.110	.399	.509
180	.389	.01654	190	190	72.5	244	316.5	.125	.381	.506
200	.660	.01671	115.4	115.4	82	240	322	.141	.364	.505
250	2.02	.01715	40.2	40.2	111	228.5	339	.183	.321	.506
300	5.17	.0175	16.3	16.3	137	218	357	.221	.288	.509
350	11.8	.0180	7.68	7.70	170	206	376	.260	.255	.515
363.9	14.7	.0181	6.28	6.30	177	203	380	.271	.246	.517
400	24.2	.0185	3.86	3.88	200	194	395	.295	.227	.522
450	46.2	.0191	2.11	2.13	232	181	413	.329	.199	.530
500	82.0	.0197	1.23	1.25	265	169	433	.364	.176	.540
550	130	.0203	.750	.770	295	153	448	.397	.152	.549
600	206	.0217	.470	.492	325	137	462	.429	.129	.558
650	300	.0230	.296	.319	356	117	473	.463	.106	.569
700	420	.0247	.187	.212	389.5	96.5	486	.498	.083	.581
750	590	.0277	.0913	.125	428	65.5	493.5	.538	.054	.592
798.1	769	.0472	0	.0472	487	0	487	.586	0	.586

TABLE II

Superheated Gaseous Aniline

Pressure		Prop.	Temperature °F																
In. Hg	Psia		250	300	350	400	450	500	550	600	650	700	750	800	850	900	950	1000	1500	2000
1	0.49	V	166.4	178.1	190.1	201.5	213	225	237	248	260	272	283.8	295.5	307.5	318.6	330.2	342.7	460	576
		H	339	357	376	396	417	439	462	486	510	535	561	588	615	643	671	700	1013	1362
		S	.536	.561	.585	.609	.633	.657	.680	.703	.725	.747	.769	.791	.812	.833	.854	.874	1.059	1.217
5	2.45	V		35.5	37.8	40.1	42.4	44.8	47.2	49.4	51.7	54.1	56.4	58.8	61.1	63.8	66.1	68.5	92	115.2
		H		357	376	396	417	439	462	486	510	535	561	588	615	643	671	700	1013	1362
		S		.527	.551	.575	.599	.623	.646	.669	.691	.713	.735	.757	.778	.799	.820	.840	1.025	1.183
10	4.91	V		17.7	18.9	20.15	21.1	22.25	23.45	24.7	25.86	27.1	28.1	29.4	30.6	31.8	33.0	34.2	46	57.6
		H		357	376	396	417	439	462	486	510	535	561	588	613	643	671	700	1013	1362
		S		.511	.535	.560	.584	.608	.631	.654	.676	.698	.720	.742	.763	.784	.805	.825	1.011	1.168
15	7.37	V			12.52	13.30	14.1	14.84	15.63	16.40	17.16	17.92	18.70	19.5	20.2	21.1	22.0	22.8	30.6	38.4
		H			376	396	417	439	462	486	510	535	561	588	615	643	671	700	1013	1362
		S			.525	.550	.574	.598	.621	.645	.667	.689	.711	.733	.754	.775	.796	.816	1.001	1.155
20	9.82	V			9.36	9.91	10.5	11.08	11.67	12.30	12.80	13.46	14.02	14.62	15.2	15.82	16.42	17.03	23.0	28.9
		H			376	396	417	439	462	485	510	535	561	588	615	643	671	700	1013	1362
		S			.518	.544	.568	.592	.615	.638	.661	.683	.705	.727	.748	.769	.790	.810	.995	1.153
25	12.28	V				7.90	8.35	8.81	9.29	9.84	10.34	10.71	11.18	11.62	12.0	12.64	13.12	13.62	18.35	23.1
		H				396	417	439	462	485	510	535	561	587	614	643	671	700	1013	1362
		S				.538	.563	.587	.610	.633	.655	.677	.700	.722	.743	.764	.785	.805	.990	1.148
29.9	14.7	V				6.58	7.00	7.33	7.72	8.21	8.55	8.95	9.34	9.72	10.2	10.57	10.93	11.43	15.32	19.23
		H				396	416	439	462	485	510	534	561	587	614	642	670	699	1013	1362
		S				.534	.558	.583	.606	.629	.651	.673	.696	.718	.739	.760	.781	.801	.986	1.144
Psia																				
20		V				4.80	5.18	5.36	5.65	5.98	6.26	6.59	6.84	7.13	7.48	7.74	8.06	8.40	11.25	14.13
		H				395	415	438	461	484	509	533	560	587	614	642	670	699	1013	1362
		S				.527	.552	.576	.600	.623	.645	.667	.689	.711	.732	.754	.775	.795	.980	1.138
30		V					3.33	3.52	3.71	3.96	4.15	4.36	4.55	4.74	.496	5.15	5.37	5.59	7.51	9.42
		H					414	437	460	484	509	531	560	586	614	642	670	699	1012	1361
		S					.542	.566	.590	.613	.636	.658	.680	.702	.723	.744	.765	.785	.971	1.129
40		V					2.48	2.61	2.75	2.96	3.10	3.26	3.39	3.54	3.70	3.85	4.05	4.18	5.62	7.06
		H					413	436	458	483	507	530	560	586	613	641	669	699	1012	1361
		S					.534	.559	.583	.607	.629	.652	.674	.696	.717	.738	.759	.779	.965	1.123
50		V						2.07	2.18	2.355	2.45	2.59	2.70	2.85	2.95	3.07	3.20	3.34	4.49	5.65
		H						435	457	482	506	529	558	585	613	641	669	698	1012	1361
		S						.553	.578	.601	.624	.646	.669	.691	.712	.733	.754	.774	.960	1.118
60		V						1.702	1.793	1.930	2.02	2.14	2.24	2.34	2.45	2.54	2.66	2.77	3.74	4.71
		H						434	456	481	504	527	557	585	612	640	669	698	1012	1361
		S						.549	.573	.597	.619	.642	.664	.687	.708	.729	.748	.770	.955	1.114
70		V						1.441	1.520	1.648	1.72	1.833	1.91	1.995	2.09	2.17	2.27	2.37	3.21	4.03
		H						433	455	480	503	526	556	584	612	640	668	698	1012	1361
		S						.545	.569	.593	.616	.638	.661	.683	.705	.726	.747	.767	.952	1.111

TABLE II — *Continued*

SUPERHEATED GASEOUS ANILINE

PRESSURE PSIA	PROP.	TEMPERATURE °F																	
		250	300	350	400	450	500	550	600	650	700	750	800	850	900	950	1000	1500	2000
80	V						1.243	1.310	1.410	1.492	1.587	1.653	1.732	1.82	1.893	2.26	2.07	2.80	3.53
	H						432	453	479	501	524	554	584	611	640	668	697	1011	1361
	S						.540	.565	.590	.613	.635	.658	.680	.701	.722	.747	.764	.949	1.129
90	V							1.150	1.248	1.319	1.420	1.462	1.534	1.61	1.675	1.75	1.83	2.48	3.14
	H							452	477	500	523	552	583	611	639	668	697	1011	1361
	S							.563	.587	.610	.633	.655	.678	.699	.720	.744	.761	.947	1.106
100	V							1.023	1.115	1.174	1.257	1.310	1.373	1.444	1.500	1.572	1.638	2.23	2.82
	H							451	476	499	522	550	583	610	639	667	696	1011	1361
	S							.560	.584	.608	.631	.653	.676	.697	.718	.739	.759	.945	1.104
120	V							.836	.910	.969	1.036	1.079	1.148	1.197	1.244	1.302	1.360	1.86	1.76
	H							449	473	497	521	549	582	609	638	666	696	1011	1360
	S							.554	.579	.602	.626	.649	.671	.693	.713	.735	.755	.941	1.099
140	V								.766	.816	.874	.920	.961	1.018	1.060	1.107	1.161	1.59	1.562
	H								471	495	518	547	581	608	637	666	695	1010	1360
	S								.574	.598	.622	.645	.668	.689	.710	.732	.752	.938	1.096
160	V								.654	.698	.752	.796	.833	.896	.920	.962	1.008	1.39	1.406
	H								468	492	515	544	579	608	636	665	694	1010	1360
	S								.569	.594	.618	.641	.664	.686	.707	.726	.748	.935	1.093
180	V								.506	.610	.661	.700	.732	.772	.811	.849	.896	1.23	1.120
	H								462	489	512	542	578	607	635	664	693	1009	1359
	S								.560	.590	.614	.638	.661	.682	.703	.725	.745	.932	1.088
200	V									.543	.558	.620	.653	.690	.723	.760	.794	1.106	.933
	H									487	510	541	577	605	634	663	693	1009	1358
	S									.587	.611	.635	.658	.680	.701	.723	.743	.929	1.083
250	V									.414	.447	.479	.508	.539	.569	.596	.628	.879	.799
	H									481	505	536	574	603	632	661	691	1008	1357
	S									.579	.604	.629	.652	.673	.695	.717	.735	.924	1.076
300	V									.325	.356	.387	.411	.440	.464	.487	.515	.731	.698
	H									475	499	531	572	600	630	659	689	1007	1357
	S									.569	.597	.622	.646	.668	.690	.712	.732	.916	1.072
350	V										.290	.316	.341	.367	.389	.410	.434	.622	.620
	H										493	527	567	597	627	657	687	1006	1356
	S										.591	.617	.642	.664	.686	.708	.728	.913	1.070
400	V										.234	.262	.289	.310	.333	.352	.373	.542	.556
	H										488	522	563	594	625	655	687	1005	1355
	S										.584	.612	.637	.660	.682	.704	.724	.911	1.067
450	V											.220	.245	.268	.288	.307	.326	.479	.505
	H											516	559	590	622	652	683	1004	1355
	S											.607	.633	.656	.679	.701	.722	.907	1.065
500	V											.185	.209	.232	.250	.270	.288	.429	.556
	H											508	554	587	619	650	680	1003	1355
	S											.598	.628	.651	.674	.697	.717	.907	1.067
550	V											.152	.1793	.203	.222	.240	.255	.389	.505
	H											501	549	583	616	647	678	1001	1355
	S											.593	.624	.647	.671	.694	.715	.905	1.065
600	V												.1537	.180	.201	.215	.230	.354	.462
	H												543	578	612	644	676	1001	1354
	S												.620	.644	.668	.691	.712	.904	1.063
650	V												.1306	.158	.177	.193	.209	.326	.425
	H												532	573	608	642	673	1000	1353
	S												.614	.640	.664	.688	.709	.901	1.061
700	V												.1094	.140	.159	.1747	.1893	.300	.394
	H												524	569	605	639	670	998	1353
	S												.608	.635	.661	.685	.705	.899	1.059
769	V												.0472	.119	.139	.1538	.1674	.272	.359
	H												487	560	598	634	667	997	1352
	S												.586	.629	.656	.681	.702	.897	1.057
800	V												.0378	.1087	.1293	.1451	.1582	.261	.343
	H												466	553	595	632	665	997	1351
	S												.561	.626	.654	.679	.699	.895	1.056
900	V												.0339	.0771	.1052	.1212	.1345	.228	.305
	H												452	529	584	625	659	995	1350
	S												.554	.607	.646	.673	.696	.893	1.053
1000	V												.0325	.0554	.0854	.1018	.1155	.205	.273
	H												449	513	571	616	652	993	1349
	S												.552	.591	.632	.665	.691	.890	1.051
2000	V												.0285	.0305	.0332	.0374	.0423	.0958	.1344
	H												433	480	522	564	605	975	1339
	S												.539	.569	.597	.626	.651	.868	1.032
4000	V												.0250	.0261	.0270	.0281	.0301	.0500	.0694
	H												430	474	511	547	585	950	1327
	S												.529	.555	.575	.608	.632	.844	1.013
6000	V												.0234	.0240	.0248	.0257	.0269	.0387	.0510
	H												432	473	509	545	581	942	1318
	S												.519	.547	.572	.600	.626	.831	1.001
8000	V												.0222	.0231	.0239	.0250	.0256	.0334	.0425
	H												437	477	514	549	584	941	1317
	S												.518	.544	.572	.600	.624	.825	.995
10000	V												.0219	.0223	.0229	.0236	.0244	.0311	.0377
	H												441	482	517	554	589	946	1320
	S												.514	.540	.568	.595	.618	.818	.987

solution was questionable. Also, since the pressure-volume-temperature data had been determined by generalized compressibility factors, and since charts of pressure-correction versus reduced pressure for "general" gases exist in the literature, such a solution is unnecessary. The best chart of this kind found was one given by York and Weber.[45] In this chart $(\Delta H)M/T_c\Phi$ was plotted against P_r to give a family of constant T_r lines. Here, ΔH represents the reduction of enthalpy due to change in pressure, M converts this change to a molar basis, and Φ is a correction found necessary to make the data generalize properly: $\Phi=(T_c/370)^n$. Values for the exponent n were determined empirically on the basis of a large number of compounds. No values, however, were given below the critical point. Thus enthalpies down to the 800° F isotherm were established.[9] Below the critical temperatures no Φ exists, necessitating the following extrapolation: The 800° F enthalpy isotherm was drawn in on a pressure-enthalpy plot.[9] Here was located the critical enthalpy. At the triple point pressure, the zero pressure enthalpies were marked in. Since the enthalpy did not vary more than 1 Btu/lb below the saturation pressure until a boiling point of about 400° F was reached, the isotherms could be drawn in straight vertical lines below this temperature. The points where these lines run into the saturation line were also determined since, at the temperature of each, the vapor pressure was known. These points could now be connected to form the lower portion of the saturated vapor line. From here, with knowledge of the approximate shape that this line had to assume from other substances, and the critical point, the complete saturated vapor line could be interpolated. As the latent heats of vaporization had also been determined, the saturated line could next be drawn. Finally the remaining enthalpy isotherms which had been drawn vertically to about 10 psia, could be curved to meet the saturated vapor line at the proper pressure, a further interpolation.

This treatment is thought, at the worst, to be accurate within 2 per cent of the values which would have resulted had accurate low-temperature Φ values been available.

Enthalpies in the liquid range were determined[9] over a limited temperature range by use of another generalized method presented by Watson.[30] Watson has generalized the difference between enthalpy at the given pressure and temperature, and that at the critical pressure and the given temperature.

Some measured values of C_p have been reported for liquid aniline[17,46-50] at atmospheric pressure over the limited range of 0° F to 250° F.

Entropy

Entropy above the chosen standard state[9] may be expressed by the equation,

$$S=\frac{\Delta H_{v0}}{T_0}+\int_{T_0}^{T}(C_{p0}/T)dT-\int_{P_0}^{P}\left.\frac{\partial V}{\partial T}\right|_p dP. \quad (14)$$

The first term was readily evaluated, since the standard state latent heat and temperature were known, i.e., 273/479=0.569 Btu/(lb) (°F). The second term was readily obtained by graphical integration, C_{p0} being previously evaluated over the complete range of temperatures. The third term, or the pressure correction, was evaluated by use of another generalized plot given by York and Weber.[45]

Entropy of liquid aniline was also estimated for a few conditions[9] by another of Watson's expansion factor methods.[30]

Parks and Huffman[51] present entropy data at low temperatures and also a heat of formation for aniline.

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(Continued on page 28)

SEQUENTIAL WORK SAMPLING *

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Work sampling is a simple statistical technique used to evaluate how people use their time on their jobs. It is done in the following manner: First, the activities of a person, or group of persons engaged in similar work, are listed. For a secretary, the activities could be typing, filing, using the telephone, etc. An observer then looks at each of the subject workers at random times and enters a tally mark after the activity he sees being done at that instant. After many observations, the tally marks of each activity are counted. Time-utilization ratios are found by dividing the number of tally marks after each activity by the total number of marks.

Utilization ratios furnish valuable information for management in measuring the effectiveness of management or workers. For instance, a work sample taken of a group of production workers may show that delays are excessive. This fact may be obvious to someone familiar with the production operations, but it is very difficult for anyone to *measure* these delays from cursory observation.

In the last three years the technique has gained widespread use, including that of sampling the activities of nurses and engineers, and promises to become one of the more valuable tools of the industrial engineer. At the University, it is now included in the motion and time-study course.

Work Sampling

The statistics involved in work sampling are those involved in general sampling theory. When we take many samples at random from a population of a known proportion, we expect the sample proportions to disagree with the population proportion in conformity with binomial distribution. In work sampling we assume that the probability of observing a worker engaged in an activity is equal to the proportion of his time that the activity consumes. We specify that observations are to be made at random times. Since utilization ratios are determined from a sample, the usual sampling errors are present, and hence we ask, "How reliable are these utilization ratios we have determined?"

To answer this question from a statistical viewpoint, we apply the equation for the standard error of sampling from a proportion to the work-sampling situation:

$$\sigma_p = \sqrt{p\,(1-p)/N}\,, \qquad (1)$$

where

σ_p = the standard error of a proportion,
p = the probability of making an observation of an activity,
N = the total number of observations made.

As in any other random sampling situation, the size of the sample we take has a direct effect on our confidence that the sample is giving reliable information. In the case of work sampling we assume that the lot size is infinitely large. Considering the time utilization ratios determined by a work sample, we may say that we have a 90 per cent confidence that these ratios represent the true utilization ratios of the workers within some variation or tolerance that we can calculate. This plus or minus tolerance may be represented by the symbol B. The 90 per cent confidence level is equivalent to 1.645 standard errors of a normal distribution. We may determine a value for B as equal to 1.645 standard errors when using a sample size of N total observations and a proportion equal to the utilization ratio of an activity. The following symbols are used:

n = the number of observations made of an activity with a subscript denoting a particular activity,
N = the total number of observations made for all activities, or the sample size,
R = the utilization ratio for an activity $= n/N$,
B = the ratio tolerance, plus or minus from R.

Then, since

$$1.645\,\sigma_R = \sqrt{2.71R\,(1-R)/N}$$

$$B = \sqrt{2.71R\,(1-R)/N}\,. \qquad (2)$$

To illustrate the use of the equations thus far presented, suppose that a work sample has been taken, that 280 observations have been made of a

*From a paper presented by the author at the Regional Conference of the American Society for Quality Control, University of Washington, May 9, 1953.

certain activity, and that a total of 2,000 observations have been made of all activities. Then $R=n/N=280/2{,}000$ or 0.14. Applying Eq (2) for the tolerance, then $B=\sqrt{2.71\ (.14)\ (.86)/2000}=\sqrt{0.000163}=0.0128$.

The utilization ratio may now be stated as $R=0.14\pm0.013$. This means that we have a 90 per cent confidence that the true ratio for the worker was somewhere between 0.127 and 0.153, but most likely, 0.14. If the value of N had been smaller, the value of B would have been larger.

Whether or not we are concerned with this amount of variation depends upon what action may be taken by management as a result of having this information.

The necessity of taking large samples to obtain acceptable tolerances is one of the greatest blocks to more extensive use of work sampling. To illustrate this problem more clearly, suppose we are sampling the work of 10 people engaged in similar activity and we make 10 random observations of each during each day. We will collect 100 observations per day for the sample. In a period of a normal work week we will have 500 observations and in a month, approximately 2,000 observations. A sample size of 2,000 gives reasonable tolerances, but the ratios determined represent the activities of a month with little or no reliable information about daily or weekly variations in any one activity. Management must respect this possible error in acting upon work-sampling information. With 40 subjects instead of 10, we could get the same sample size in a week and perhaps show significant differences in ratios from week to week, but, because few organizations have 40 workers in similar activities and the sample does not distinguish between individuals, this result also may be unsatisfactory. The application of work sampling may be greatly extended when fewer total observations are required for a given tolerance and when observations may be taken much more frequently than about 10 per day per person.

Sequential Work Sampling

Sequential work sampling overcomes these disadvantages. Under this plan, observations are made at regular intervals, let us say, 5 minutes apart, instead of at random times. This sampling interval will yield 96 observations per person sampled per 8-hour day. Now to ascertain the error and bias of a sequential work sample.

Thorough examination of a worker's activities will reveal two characteristics of importance to the statistical analysis of work sampling. First, the separate events of work that are compounded to make up an activity begin at random times during a regular sampling interval if the interval is short enough, as illustrated by the situation of the telephone ringing on your desk. Although you may not receive telephone calls at random times during the day, any one telephone call will begin at a random time within, say, a 5-minute interval of time during the day. A telephone call will vary in length so that it will end at some random time within the same interval or one subsequent. In the light of this characteristic, it seems possible to sample at regular intervals and yet obtain a random, unbiased sample.

The second important characteristic of worker activity lies in the way it is classified. Activities are distinguished by two general types: basic activities and interrupter activities. A simple illustration will show the difference between these two types. Consider a secretary doing normal office work including answering the telephone. She may type on a letter for several minutes at a time and stop only to answer the telephone. Activities such as typing may be called basic activities and those similar to answering the telephone may be called interrupter activities. The amount of time used for an *event* of a *basic* activity is largely dependent upon the amount of interruption and, hence, is dependent upon the nature of the job. The amount of time used for an *event* of an *interrupter* activity is nearly independent of the over-all nature of the job and is closely related to the nature of the activity or the nature of an individual event of the activity. This second characteristic has statistical importance because it determines the probability of making an observation of an *event* of an activity and thus determines the probability of observing the activity. It can be illustrated by again considering the activities of a secretary. Assume we are making observations every 5 minutes and that one of our listed activities is for telephone calls. Assuming that somehow we have determined that the average telephone call takes 4 minutes, then the probability that we would observe the secretary in the act of a telephone call is *not* the proportion of her total time that she spends on the telephone activity but, instead, is equal to the proportion of the sampling interval that the telephone call consumes. In other words, the actual probability of observing this activity is an effective probability dependent upon the average time for an event of the activity. In the example given, the effective probability is 4/5 minutes or 0.80.

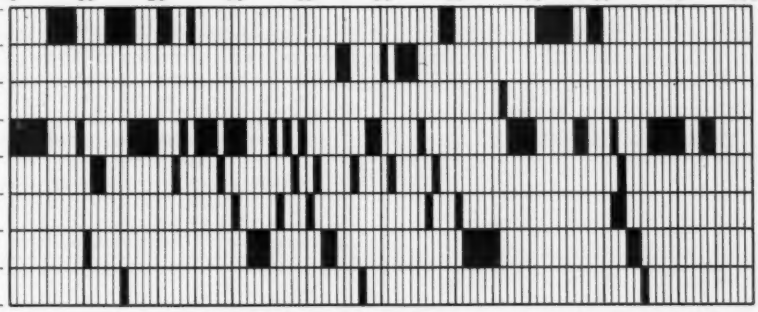
The estimate of the accuracy of a utilization ratio for an activity is changed when we can determine

WORK SAMPLING RECORD

Job Sampled_____ Secretary_____ Operator:_____ N.A.N._____ File No._____

Observer:_____ B.W.O._____ Dates:_____ Page_____ of_____

Remarks_____ Interval: _____ 5 min._____



Activity	*n*	*R*	*p'*
Typing	20	.208	.60
Filing	6	.063	.500
Dictation	1	.010	.010
Misc. Prod.	36	.375	.528
Telephone	10	.104	.104
Inquiries	7	.073	.145
Personal	13	.135	.615
Idle & A.D.	3	.031	.031
TOTALS	96		

FIG. 1. WORK-SAMPLING RECORD OF A SECRETARIAL JOB

the effective probability of observing the activity. We can calculate the effect of knowing the effective probability by applying the equation for standard error when sampling from a proportion. The following symbols are used:

Y = the number of events that are compounded to make up an activity,

R = the utilization ratio n/N,

p' = the effective probability of making an observation of an event,

P_n = the probability of making n observations from Y events having an effective probability of p'.

Then,

$$P_n = \frac{Y!}{n!\,(Y-n)!}\,(p')^n\,(1-p')^{Y-n}.$$

The standard error of this probability distribution is

$$\sigma_n = \sqrt{Yp'\,(1-p')}.$$

The number of times that the activity will be observed is n, and an estimate of n from Y events is $n = Yp'$. Substituting this in the standard error equation yields

$$\sigma_n = \sqrt{n\,(1-p')}.$$

Observing the activity n times will give $R = n/N$, so we may say that $n = NR$. Also, $(\sigma_R) = (\sigma_n)/N$. Substituting these equalities in the above equation for σ_n, we have

$$N\sigma_R = \sqrt{NR\,(1-p')},$$

$$\sigma_R = \sqrt{R\,(1-p')/N}.$$

For the 90 per cent sampling confidence level, the value of the tolerance, B, equals the value of $1.645\sigma_R$. This may be substituted in the above equation for B:

$$B = \sqrt{\frac{2.71R\,(1-p')}{N}}. \qquad (3)$$

Determining the Accuracy of Utilization Ratios

In random work sampling, Eq (3) applies by letting

$$p' = R. \qquad (4)$$

In sequential work sampling, the time-study method of determining p' uses the following equation:

$$p' = i/m, \qquad (5)$$

where

i = average time for an event of an activity,

m = sampling interval.

For activities of the interrupter type, i may be determined by conventional stop-watch time studies. However, values of p' determined from i must be treated as estimates only, in that the time for one worker to perform an event may be different from that required by another, in other surroundings.

A better method for determining p' is available when the time for an event frequently exceeds the sampling interval. This situation is revealed during sequential sampling, when several tally marks in a row are recorded for the same activity, usually indicating that an event has consumed more than one sampling interval and that there is a concentration of that particular activity during that part of the day.

As an illustration, a sequential work sample of a secretary's activity was taken with a sampling interval of 5 minutes. Figure 1 shows the record of that sample. Notice that this record shows concentration of the typing activity at definite times during

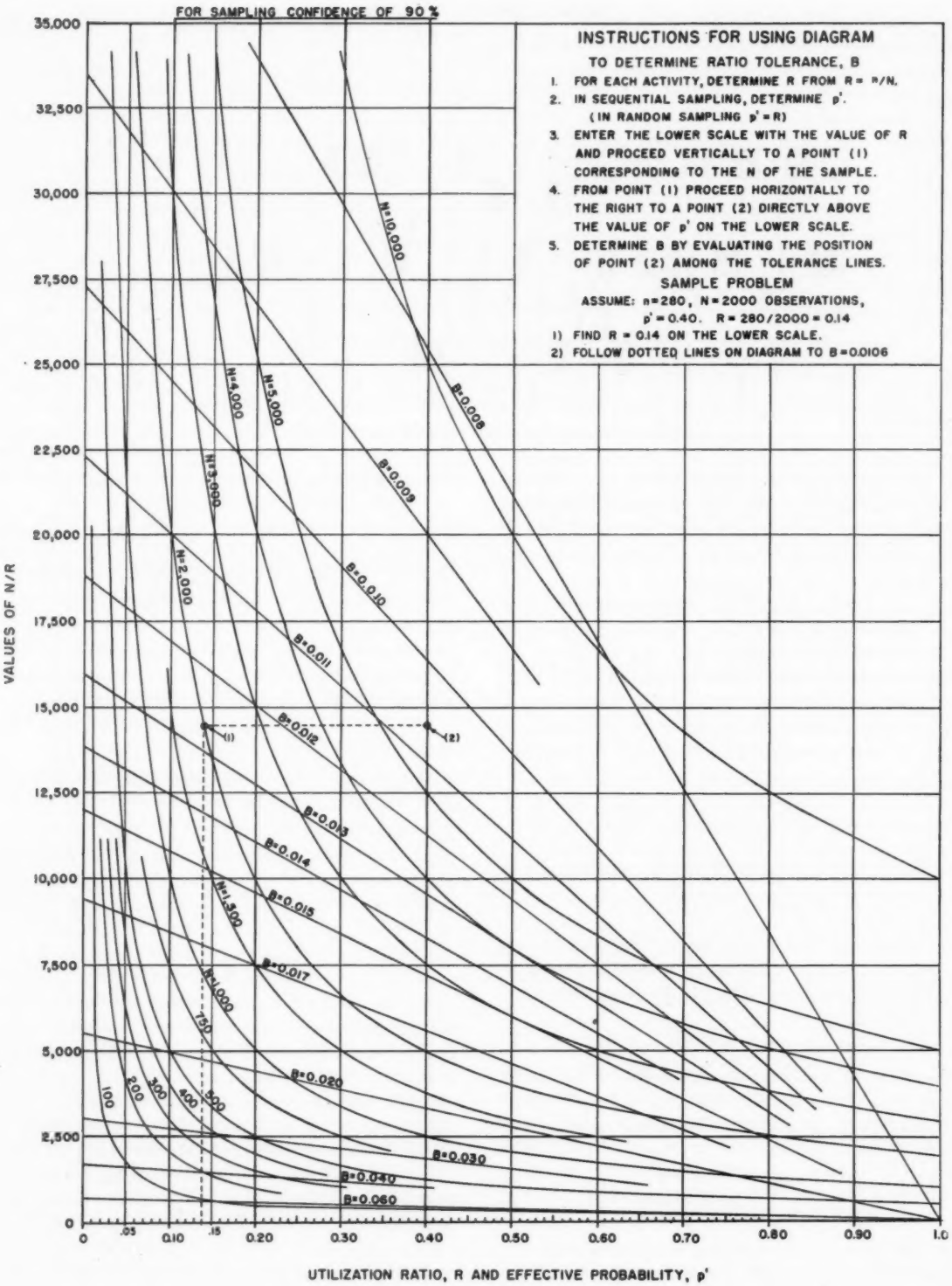

FOR SAMPLING CONFIDENCE OF 90 %
INSTRUCTIONS FOR USING DIAGRAM
TO DETERMINE RATIO TOLERANCE, B
1. FOR EACH ACTIVITY, DETERMINE R FROM R = n/N.
2. IN SEQUENTIAL SAMPLING, DETERMINE p'. (IN RANDOM SAMPLING p' = R)
3. ENTER THE LOWER SCALE WITH THE VALUE OF R AND PROCEED VERTICALLY TO A POINT (1) CORRESPONDING TO THE N OF THE SAMPLE.
4. FROM POINT (1) PROCEED HORIZONTALLY TO THE RIGHT TO A POINT (2) DIRECTLY ABOVE THE VALUE OF p' ON THE LOWER SCALE.
5. DETERMINE B BY EVALUATING THE POSITION OF POINT (2) AMONG THE TOLERANCE LINES.
SAMPLE PROBLEM
ASSUME: n=280, N=2000 OBSERVATIONS, p' = 0.40. R = 280/2000 = 0.14
1) FIND R = 0.14 ON THE LOWER SCALE.
2) FOLLOW DOTTED LINES ON DIAGRAM TO B=0.0106
VALUES OF N/R
UTILIZATION RATIO, R AND EFFECTIVE PROBABILITY, p'
N=10,000
N=5,000
N=4,000
N=3,000
N=2,000
N=1,500
N=1,000
750
500
400
300
200
100
B=0.008
B=0.009
B=0.010
B=0.011
B=0.012
B=0.013
B=0.014
B=0.015
B=0.017
B=0.020
B=0.030
B=0.040
B=0.060
(1)
(2)

FIG. 2. WORK-SAMPLING GRAPH

the day. In such a case, the effect of this concentration on the effective probability, p', can be determined by using the average number of observations made in a row for that activity during the taking of the sample. In Fig. 1 the activity of typing shows 20 observations made in 8 groups. Let the symbol $\bar{a}$ (a bar) equal the average number of tally marks in a row. Then for typing, $\bar{a}$ equals 20 observations divided by 8 groups, or 2.50 observations per group. The equation that expresses this relationship is

$$\bar{a}=n/G,$$

where

n = number of marks for the activity,

G = number of groups of marks, one being the minimum sized group.

From formal mathematical expressions of probability we can derive the following expression for the average number of like things that will be drawn in a row from a proportion:*

$\bar{a}$ = the average number of things drawn in a row in random sampling from a proportion,

p = the proportion of like things in the population from which the sample is drawn.

The drawing of things other than what we are interested in has no effect on $\bar{a}$. This expression is fitting to the sequential work-sampling situation where p', or the effective probability of observing an event, is the proportion in question. Conversely, if we know the value of $\bar{a}$, we can determine the value of the proportion. From the two expressions,

$$\bar{a}=1/(1-p') \quad \text{and} \quad \bar{a}=n/G,$$

an expression for p' can be stated as follows:

$$p'=1-(G/n). \tag{6}$$

The value of p' for the typing activity in our example is $1-(8/20)$ or 0.60. The value of R for this activity is 0.208. The value of B, using p' and substituting in Eq (3), is

$$B=\sqrt{\frac{2.71\ (0.208)\ (1-0.60)}{96}}=0.0485.$$

Neglecting the effective probability information and treating the sample as purely random yields

$$B=\sqrt{\frac{2.71\ (0.208)\ (1-0.208)}{96}}=0.0682.$$

The confidence in the resulting ratio, considering the sample as purely random, is poorer by $0.0682-0.0485$ or 0.0197. This may be expressed as $0.0197/0.0485$ or 40 per cent poorer confidence. We now have two ways of determining p' in sequential work sampling:

$$p'=i/m \quad \text{(by time-study)}, \tag{5}$$

$$p'=1-(G/n) \quad \text{(from sample)}. \tag{6}$$

*See the author's thesis for the degree of M.S. in Mechanical Engineering, University of Washington Press, Seattle, 1953.

Equation (5), which is estimated before the sample is taken, is less reliable than Eq (6) where a post-sample estimate is made. However, the latter, which involves group counting, is of little help for *interrupter* activities where the events are usually short and occur at random. Note that concentrations of such activities are not apparent on the work-sampling record (Fig. 1), as illustrated by the telephone activity.

It is also important to note that the value of p' can never actually be *less* than R, even though the equations say so. This also is illustrated by the telephone activity which shows 10 marks and 9 groups. Then from $p'=1-(G/n)$, $p'=1-(9/10)$ or 0.10. In cases where p' is estimated to be less than R, therefore, it is necessary to use Eq (4), $p'=R$, which was used in random work sampling.

With the increased reliability of the utilization ratios as determined by a sample, it now becomes practical to apply control charts to worker activity in certain areas. To get a significant distinction between the ratios as compared from one day to another, small tolerances must result for the ratios determined by one day of sampling. This demands a large number of observations and a high effective probability. These conditions can be met by using the sequential work-sampling plan with short sampling intervals or by the random sampling plan with a large group of similar workers. Sequential work sampling is particularly appropriate for sampling the work of a few people engaged in like jobs.

Work-Sampling Diagram

For any given sampling confidence, the equations for determining the ratio tolerances can be solved graphically. This graphical expression of the relationship of B to R, p', and N is shown by Fig. 2, a work-sampling diagram for a sampling confidence of 90 per cent. Instructions for using the diagram are given in the upper right-hand corner. Tolerances for random samplings are determined at point (1), and for sequential sampling at point (2). Two preliminary calculations are required for using the diagram:

(1) Determine the utilization ratios for each activity from the equation, $R=n/N$,

(2) Determine the values of effective probability for each activity by the most appropriate of Eq (4), (5), and (6):
$p'=R$; $p'=i/m$;* $p'=1-(G/n)$.

With this diagram, mistakes are less likely to occur, and with a little instruction a clerk can do the job.

*Equation (5), the time-study method, is seldom used.

NORTHWEST ROAD CONFERENCE TO BE HELD ON CAMPUS

THE SEVENTH NORTHWEST CONFERENCE ON ROAD BUILDING will be held in More Hall, on February 17, 18, and 19, 1954. Subjects to be discussed formally, or by panels, include Oregon and Washington highway problems, highway financing, urban expressways, county road needs, aerial surveys, swelling sub-grade soils, roadside development, asphaltic road surfacing and performance, the engineer's notebook (which will include descriptions of several unusual engineering situations connected with road building), and concrete and timber structures. Speakers especially qualified in their fields from Oregon, Washington, California and the East will be on the program. The highway directors of both Washington and Oregon, Mr. W. A. Bugge and Mr. R. H. Baldock, will address the group. Speakers from the Civil Engineering Department of the University will include Prof. M. I. Ekse, who will discuss methods of applying the WASHO road-test data to roads and streets in Washington, and Prof. R. G. Hennes, who will speak on the work of the Washington Council for Highway Research, with special reference to the current project: the allocation of highway costs.

Registration will take place in More Hall from 8:30 to 10:00 A.M., Wednesday, February 17. The registration fee of $2.00 will include a copy of the *Proceedings* of the Conference, when published. Road Building Conferences in the past have attracted a broad cross section of interest. Over 350 engineers, contractors, suppliers, and public officials attended the 1952 Conference at the University of Washington. The 1953 Conference was held at Corvallis, Oregon.

IMPORTANCE OF CROSSWIND FORCES

(Continued from page 16)

At the present time, moving wing systems gain little advantage from the attainable crosswind forces. If future developments can be made to yield the maximum advantage that is possible, aircraft of this type may have performance superior in all respects to that obtainable with screw-propelled wings. In any event, important improvements should be expected from efforts to gain this advantage.

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ASPECTS OF X-RAY DIFFRACTION

(Continued from page 9)

This account has merely given a cross section of the analytical work undertaken at the Laboratory during the past year. Studies of deformation and orientation due to metal working, solid solution determination, particle-size analysis, and a host of other uses not described here, attest the versatility of X-ray diffraction techniques. While not providing a solution to all analytical problems, they can be a powerful tool to materially assist the scientist as well as those in production.

THERMODYNAMICS OF ANILINE

(Continued from page 22)

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CORRECTION

In the October, 1953, issue of *The Trend,* Prof. F. C. Smith should have been cited as author of the technical article, "Simplified Solution of Castigliano's Theorem," Bull. Mech. Div., ASEE, Dec., 1951, which was listed under the name of Prof. S. Sergev in the report of the civil engineering publications.

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